UNIVERSIDAD LOYOLA ANDALUCÍA

DOCTORAL THESIS

Distributed estimation techniques for cyber-physical systems

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Abstract

Nowadays, with the increasing use of wireless networks, embedded devices and agents with processing and sensing capabilities, the development of distributed estimation techniques has become vital to monitor important variables of the system that are not directly available. Numerous distributed estimation techniques have been proposed in the literature according to the model of the system, noises and disturbances.

One of the main objectives of this thesis is to search all those works that deal with distributed estimation techniques applied to cyber-physical systems, system of systems and heterogeneous systems, through using systematic review methodology. Even though systematic reviews are not the common way to survey a topic in the control community, they provide a rigorous, robust and objective formula that should not be ignored. The presented systematic review incorporates and adapts the guidelines recommended in other disciplines to the field of automation and control and presents a brief description of the different phases that constitute a systematic review.

Undertaking the systematic review many gaps were discovered: it deserves to be remarked that some estimators are not applied to cyber-physical systems, such as sliding mode observers or set-membership observers. Subsequently, one of these particular techniques was chosen, set-membership estimator, to develop new applications for cyber-physical systems. This introduces the other objectives of the thesis, i.e. to present two novel formulations of distributed set-membership estimators. Both estimators use a multi-hop decomposition, so the dynamics of the system is rewritten to present a cascaded implementation of the distributed set-membership observer, decoupling the influence of the non-observable modes to the observable ones. So each agent must find a different set for each sub-space, instead of a unique set for all the states.

Two different approaches have been used to address the same problem, that is, to design a guaranteed distributed estimation method for linear full-coupled systems affected by bounded disturbances, to be implemented in a set of distributed agents that need to communicate and collaborate to achieve this goal.

Under these conditions, the first technique uses sets that are mathematically described by zonotopes and it intends to achieve the minimization of the estimation uncertainty computing adequate local and neighbour gains. The observer can be designed in independent distributed steps by means of a simple algebraic equation. An important benefit of the proposed structure is the reduction of the computational requirements concerning existing solutions.

Under the same conditions, the second technique uses sets that are mathematically described by constrained zonotopes. Periodic, multi-rate, event-based or fully asynchronous communication schemes are shown to be easily integrated with the proposed estimation structure. Particular attention was paid to the impact of transmission, depending on the different communication schemes.

The nature of all the contributions of this thesis is theoretical. However, the solutions adopted could be applied to a wide variety of distributed systems. Nevertheless, simulations and numerical results are considered to compare the proposed solutions with existing ones in the field.

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Carmelina Ierardi
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List of Abbreviations

AE	**A**nalytical **E**quation
CPS	**C**yber **P**hysical **S**ystem
DKF	**D**istributed **K**alman **F**ilter
FDI	**F**ault **D**etection and **I**solation
LMI	**Li**near **Ma**trix **I**nequality
LTI	**L**inear **T**ime **I**nvariant
PICOC	**P**opulation, **I**ntervention, **C**omparison, **O**utcome, **C**ontext
PRISMA	**P**referred **R**eporting **I**tems for **S**ystematic reviews and **M**eta-**A**nalysis
SR	**S**ystematic **R**eview

A te dedico ogni mio sforzo,
a te dedico ogni mio respiro.

Chapter 1

Introduction and Motivation

This chapter is used to define the structure and context of the thesis. Furthermore, it focuses on the objectives set and the reasons that led to its drafting. Finally, a brief breakdown and a list of publications supporting this work are presented.

1.1 Introduction to distributed estimation in cyber-physical systems

To provide context for the reader, some concepts will be explained, such as Cyber-Physical System (*CPS*), the term *distributed* and *estimation*.

1.1.1 Cyber-physical systems

Cyber-physical systems integrate computing and communication capabilities with monitoring and control of entities in the physical world. These systems are usually composed by a set of networked agents including sensors, actuators, control processing units and communication devices [16], as shown in Figure 1.1.

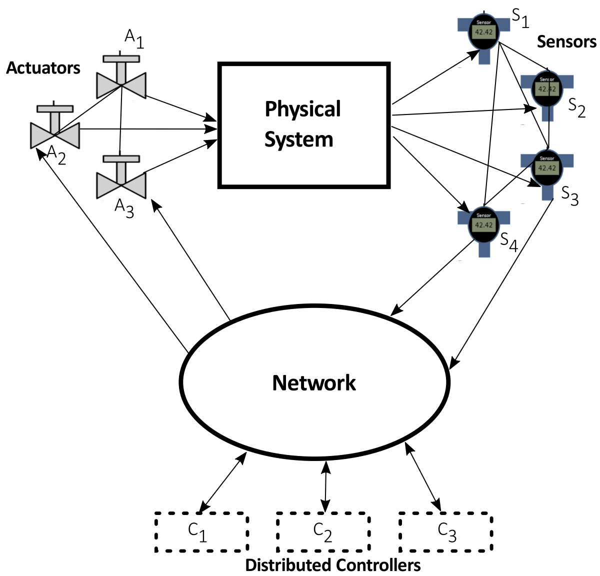


FIGURE 1.1: The architecture of cyber-physical systems [16]

On the one hand, they are composed of a physical system, in which heterogeneous subsystems are generally present, and may include people or other living beings; on the other hand, they also include embedded systems, which are generally devices that integrate measurement, processing and communication capabilities, and that in a distributed way monitor and control physical processes through communication networks. These networks, mainly wireless, make it possible to estimate in real time the variables of a cyber-physical system using estimation techniques [3], [55].

One of the difficulties presented by the CPS, which derives from their inherent complexity and heterogeneity, is the need to know or at least have a reliable estimate of the variables of the complete system, being able to monitor, supervise it and control it correctly. Given that the entities that are part of a CPS have in general different sensing, computing and control capacities, as well as access to certain local information of the complete system, depending for example on their location, it is necessary to develop coordinated strategies to be able to supervise the system in a distributed way from the devices that are integrated into it. This coordination requires some sort of communication between the agents.

The complexity considered, together with the communication problems of a real network and the coordination of the studied systems, increase the challenges and difficulties in the development of CPS [55].

1.1.1.1 Some possible applications of CPSs

The importance of CPSs does not only lie in the scientific challenge of addressing the complexity of this new type of systems, but is above all in its multiple applications, which allow the development of technologies to provide solutions to strategic problems of today's society, for example:

- Transport systems, with the development of autonomous vehicles and distributed traffic monitoring systems [52].
- Smart buildings, with the rise of sensors that allow monitoring and recording variables such as consumption, brightness or temperature, as well as robots and devices such as mobiles or tablets that can be connected to home automation elements [48].
- Intelligent electrical grids, which from distributed agents will allow knowing the status of the electrical grids, making possible a better integration of distributed power generation systems [43].
- Applications in health systems, with CPSs that allow, for example, distributed monitoring in hospital facilities [77].

1.1.2 Distributed structure

With the development of large-scale and complex systems, with wireless networks, embedded devices and agents with processing and sensing capabilities which are geographically located very far away from each other, distributed techniques are becoming increasingly important in industrial applications. In particular, distributed estimation allows estimating the value (at different points of the system) of important variables that cannot be directly measured. This makes it possible to operate and control the system in a distributed manner.

The term distributed is opposed to centralised and it is similar to decentralized. Figure 1.2 shows the schematic difference between the three types of structures. In the centralized topology (Figure 1.2 a), an intelligent network has a data fusion centre. Thus, each agent can send/receive data to/from the fusion centre respectively. Figure 1.2 b represents the decentralized case, where there is more than one fusion centre, between which communication is permitted. In this case, there is no communication among other agents. Lastly, Figure 1.2 c indicates the distributed system scheme. Indeed the agents have to communicate among them through a network sharing their estimation to obtain information about the whole system.

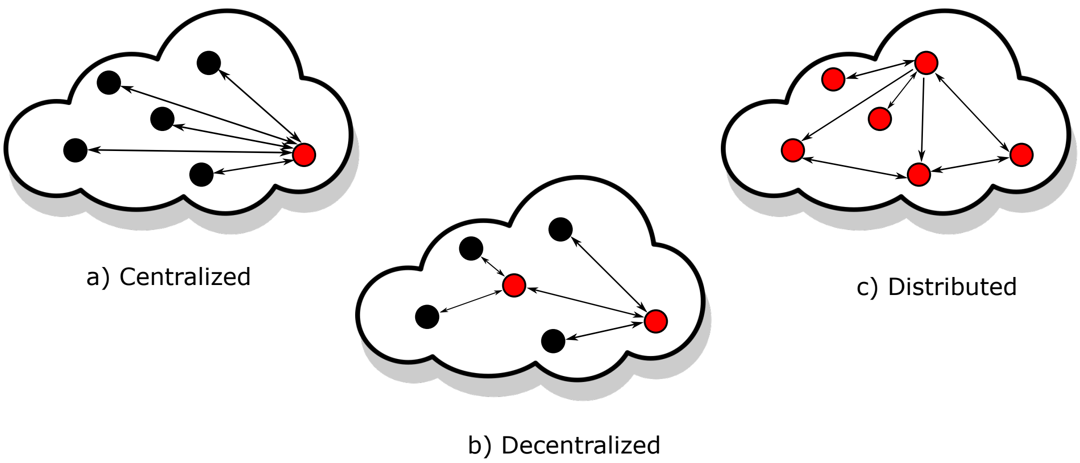


FIGURE 1.2: Differences between centralized, decentralized and distributed system scheme

Among the main advantages of a distributed structure there are [70]:

- Scalability: when the plant to be controlled has large dimensions, distributed architecture offers the possibility of introducing a network of easily expandable sensors. Indeed the scalability describes the ability of the system to dynamically adjust its computing performance by changing available computing resources in a wide range of sizes and configurations.
- Flexibility: distributed structure adjusts to any type of plant, allowing the interconnection of different intelligent devices that share a common communication protocol.

- Fault tolerance: distributed design is more tolerant to faults. That is because when one or more central owners or servers fail, the others can continue to provide data access to devices. A distributed system is safe from an independent failure of individual components.

However, one of the main potential problems of distributed systems is related to the communication channel. In fact, it can present problems such as communication failures, delays sending packets, etc. Another problem is caused by the lack of global information in all devices involved in the problem. These represent the major disadvantages of distributed design.

1.1.3 State estimation

The definition of estimation indicates a rough calculation of the value, number, quantity, or extent of something. In the field of systems theory and control theory, the state estimation performs a mathematical analysis that provides an estimation of the internal state of a given real system. Starting from the input and output measurements of the real system this method relies on: (see Figure 1.3):

- knowledge of system and measurement dynamics,
- presumed statistics of system noises and measurement errors and
- initial condition information.

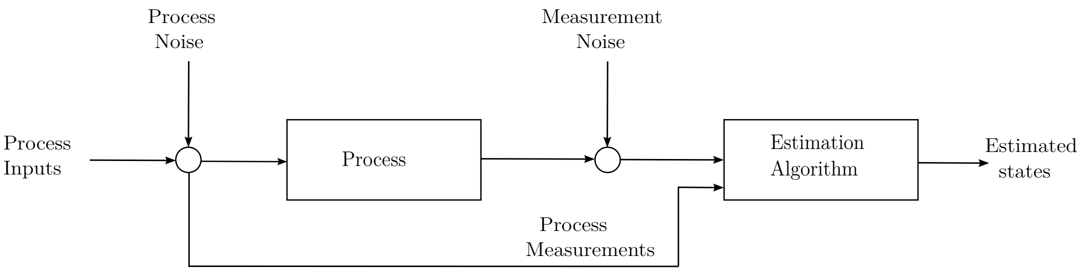


FIGURE 1.3: Block diagram of state estimation scheme

Knowing the system state is necessary to solve many control theory problems, for example, stabilizing a system using state feedback laws. In most practical cases, however, the physical state of the system cannot be determined by direct observation. Instead, the indirect effects of the internal state are observed through system outputs. In this sense, a state observer is a system that provides an estimate of the internal state of a real system, from measurements of the input and output of a deterministic dynamical system (no randomness involved in the development of future states of the system).

The approaches used to design observers can be classified according to how they deal with uncertainties. Based on the classification carried out in [23], two paradigms can be used to model uncertainties:

- **Stochastic uncertainties:** the stochastic one relies on probability theory and mainly deals with random variables. Usually, assumptions about their probability distribution are required. For instance, state estimators based on Kalman filtering rely on covariance matrices to model Gaussian state and measurement random perturbations. Though well suited to take the distribution of random noises into account, this modelling of uncertainty may be less representative when dealing with large disturbances mostly related to not well-known deterministic behaviours [23].

- **Set-membership paradigm:** the set-membership paradigm, relying on unknown but bounded uncertainties can lead to descriptions requiring no assumptions about the probability distributions. This approach is based on the construction of a compact set, that includes, with guarantee, the states of the systems that are consistent with the measured output and the bounded noise [4]. The bound of the state of the system dynamics has been considered from different perspectives among which stand out variants of ellipsoidal state sets have been proposed as well as solutions addressing robustness issues. Interval analysis has also led to state bounding algorithms, either based on set predictions/intersections resembling Kalman filtering or based on interval observers. The latter usually provides computationally efficient set-membership estimations with proven stability, but it deals with interval hulls which may be a rough enclosure of the consistent state sets [23]. Furthermore, in recent decades the study of zonotopes as a set for bounding the state of a system has increased enormously, above all due to the simple basic operations to be performed in distributed embedded systems with limited computation capabilities [75].

1.2 Motivation

The thesis is framed in the research project CyNEDIC (Cooperación y negociación entre agentes para la estimación distribuida en sistemas ciberfísicos), funded by AEI/FEDER (Agencia Estatal de Investigación y el Fondo Europeo de Desarrollo Regional), with reference TEC2016-80242-P. Among the main objectives of the project, which were partly considered and developed also within this thesis, there are:

- To carry out an exhaustive review of the distributed estimation techniques that can be applied to CPSs.

- To design distributed estimation algorithms: this phase constitutes the central part of the project (and also of the thesis), since its main objective is to develop a new generation of distributed estimators for CPSs. These new techniques must be able to adapt to systems with heterogeneous dynamics and changing structures, which will also be physically coupled in many cases.

In addition to the project, this thesis continues a line of research that had been previously developed by the ODS research group of the Universidad Loyola Andalucía.

1.3 Objectives

The main objectives of this thesis can be summarised as:

- To provide a study of the current literature on distributed estimation techniques for CPS, taking advantage of the systematic review. The methodology used in this work to compile the state of the art is still not diffused in the engineering world. For this reason, a dedicated description has been inserted in the next chapter.
- Among the conclusions of the systematic review some weaknesses emerged, i.e. there is not a great variety of distributed estimation techniques applied to CPSs. In particular, there are no estimators based on guaranteed techniques. They are based on the assumption of bounded variables within a certain range, i.e. the variables behave as compact sets. Hence the idea of introducing a brief traditional review of the state of the art in distributed set-membership estimation techniques for linear systems applied to CPS.
- A distributed set-membership estimator for linear full-coupled systems affected by bounded disturbances is presented. The estimator uses a multi-hop staircase decomposition, capturing the locally unobservable subspaces in a cascaded fashion with the information incoming from other agents involved in the network. Each agent has to find different sets for each subspace, that are mathematically described by zonotopes. The observer structure aims to minimise the estimation uncertainty computing adequate local and neighbour gains. These gains can be designed in independent and simple distributed steps, through the solution of algebraic equations.
- A distributed set-membership estimator under different communication schemes is introduced. The estimator also uses a multi-hop decomposition, decoupling the influence of the non-observable modes to the observable ones. Each agent has to find different sets for each subspace, that are mathematically described by constrained zonotopes. Periodic, multi-rate, event-based or fully asynchronous communication schemes are shown to be easily integrated with the proposed estimation structure.

1.4 Publications supporting this thesis

The following papers have been accepted or submitted for publication during the elaboration of this thesis:

Journal:

- Carmelina Ierardi, Luis Orihuela, Isabel Jurado. "Distributed estimation techniques for cyber-physical systems: a systematic review." Sensors (2019) [41]. Appendix A.
- Carmelina Ierardi, Luis Orihuela, Isabel Jurado. "A distributed set-membership estimator for linear systems with reduced computational requirements." Automatica. (Accepted). Appendix B.

International Conference:

- Carmelina Ierardi, Luis Orihuela, Isabel Jurado. "Guidelines for a systematic review in systems and automatic engineering. Case study: Distributed estimation techniques for cyber-physical systems." European Control Conference. 2018. Cyprus [38].
- Carmelina Ierardi, Luis Orihuela, Pablo Millán. "Technologies for resilient energy-aware cyber-physical systems of systems with human intervention". International Conference ICT 2020. Seville [40].
- Luis Orihuela, Carmelina Ierardi, Isabel Jurado. "A distributed set-membership estimator for linear systems considering multi-hop subspace decomposition". IFAC World Congress 2020. Virtual [74].
- Carmelina Ierardi, Luis Orihuela, Isabel Jurado, Davide M. Raimondo "A distributed set-membership estimator based on constrained zonotopes under different communication schemes". Conference on Decision and Control 2021. (Under review).

National Conference:

- Carmelina Ierardi, Luis Orihuela, Isabel Jurado. "Revisión sistemática de la literatura en ingeniería de sistemas. Caso práctico: técnicas de estimación distribuida de sistemas ciberfísicos". XXXVIII Jornadas de Automática 2017. Gijón [39].

1.5 Outline of the dissertation

The following lines present the text organisation.

In Chapter 2, a systematic review is undertaken on the techniques of distributed estimation of cyber-physical systems. Additionally, some modifications of the guidelines on systematic review existing in the literature, including the available engineering databases, inclusion and exclusion criteria, function and Boolean operators, are exposed.

Chapter 3 introduces some notation and concepts that are not in the main focus of the thesis but are crucial to understand the rest of the thesis work. The main types of sets, used in set-membership estimation, and the literature related to them are also presented. The two main sets used in the thesis and their properties are presented: zonotopes and constrained zonotopes. Furthermore, the multi-hop decomposition of the state space is introduced.

Novel formulations of distributed set-membership estimators are proposed in Chapter 4. First of all, the problem statement is presented and then solutions using two distinct approaches are outlined. The first one is a distributed set-membership estimator using zonotopes, while the second uses constrained zonotopes. Furthermore for the second approach, periodic, multi-rate, event-based or fully asynchronous communication schemes are shown to be easily integrable within the proposed estimator. For both estimators, simulations and numerical results are provided to compare the proposed solutions with other techniques in the field.

Finally, Chapter 5 includes the conclusion of the thesis, where the main achievements are drawn together with potential weaknesses, limitations, and future works.

Chapter 2

Systematic Review on distributed estimation techniques for cyber-physical systems

In the following sections the process of how to undertake a systematic review is explained, and finally the systematic review on the distributed estimation techniques for cyber-physical system is presented.

2.1 Introduction

The first step of any research work is certainly the bibliographic review on the specific theme, in order to understand not only its current state but also its evolution. Nowadays, with the development of new information and communication technologies, the amount of information available and its ease of acquisition has increased enormously, perhaps surprisingly implying that it is increasingly difficult to make accurate and selective research on a specific topic to prepare a bibliographic review. The systematic review (SR), or sometimes called systematic literature review, is presented in this context as a solution to this problem [41].

In [44], a SR is defined as a mean to evaluate and interpret all available research relevant to a particular research question, thematic area or phenomenon of interest. The SR's aim is to present a fair evaluation of a research topic using a reliable, rigorous and verifiable methodology. A SR is a form of secondary study, whereas individual studies contributing to the review are termed primary studies [44].

The thematic areas that already use this kind of review range from medicine to economics, from psychology to software engineering. However, in our area of interest, automation and control, traditional survey papers are dominant. These narratives (or traditional) reviews are usually performed by researchers with extensive experience and knowledge in the field, providing their global or general view of the topic, see for instance [10], [80], [87]. Indeed it is characterised by exploiting the experts' knowledge and their broad point of view and it is based on the interpretation, analysis and personal discussion about what other authors have said. However, it does not fit the scientific paradigm, since it does not report on the number of sources, nor on the search methods, it does not make explicit the inclusion/exclusion criteria of the studies, nor does it speak about the relevance of the same with respect to the rest of the literature, nor does it provide the reason objective evidence of reasoning, among others. On the other hand, a SR follows and is distinguished by a scientific methodology, which ensures objectivity, rigour and reliability: it follows a predefined search strategy to allow an exhaustive evaluation of it [58].

The methodology to elaborate the SR that will be used in this work is inspired on the guide proposed in the bio-science [14], [81] and computer science [35], [44] literature, accordingly modified to suit the particular requirements of our field, and follows the PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analysis) method [68]. The objective of this research is to clearly explain the different stages to follow to achieve a SR in systems and automatic engineering. As a contribution, this research proposes some modifications to the aforementioned guidelines to adapt them to the considered field: available engineering databases with the kind of search that can be done and their coverage, adapted inclusion and exclusion criteria, booleans operators for the search, definition of the boolean function, etc. As the second and main objective, this work aims to apply this methodology in order to review the distributed estimation techniques that have been applied to CPS. As already mentioned, CPS are complex systems composed of entities of different natures that interact with a given physical medium [52]. They can simultaneously have communication, computation and control capabilities and they can involve humans, animals and biological processes [87]. Distributed estimation techniques aim to know the inner state of a system by using the information provided by the measurements locally collected from the plant and the information interchanged with the rest of agents [32].

To be more precise, the aim of this SR is to get to know and compare all the techniques related to distributed estimation that has been successfully applied to those heterogeneous systems that incorporate a physical part and a cybernetic layer. To be considered for inclusion in the review, the primary studies must deal with some sort of dynamical CPS and the distributed estimators or observers must exchange some sort of information with other agents, in such a way that purely decentralised schemes (without communication) or sensor fusion techniques (all the information is gathered at a single node) are excluded. Among others features, this work is interested in the amount of information that those methods require to transmit, the type of communication protocol that needs to be implemented, and whether the design of the estimator is made in a centralized or a distributed way. These constitute, mainly, the inclusion criteria for the studies appearing in the review. At the end of this chapter, it is presented a table including all this information so that the reader may get a quick perspective on the available results.

After screening more than 2800 candidate papers, only 20 primary studies have been found to satisfy the aforementioned criteria. Afterwards, they were carefully reviewed and the following data has been collected: the sort of estimator used (Kalman filter, Luenberger observer, Bayesian filter, etc.), the design of the estimators (if decentralised or centralised), the amount of data that must be exchanged between agents, the communication protocol (all-to-all, scheduled, just with neighbours, etc.), the particular application, the inclusion of experiments or simulations and some other advantages/disadvantages. A special focus has been put on those studies that apply these methodologies to humans, animals or biological systems. In our opinion, the inclusion of such systems in the estimation loop hinders the design/performance of the observers, demanding particular attention. All this information, gathered in a feature table, is very useful to get a complete, rigorous and objective view of the reviewed topic. Finally, the research questions initially formulated are answered trying to provide a full and objective perspective of the topic [41].

2.2 Preliminary concept

The main objectives of a SR are [68]:

- Defining what is known about the topic, concept or problem in general.
- Identifying gaps and coherences of past and current literature on the chosen topic.
- Promoting the development of protocols and directives that can serve as a model.

For all these reasons, undertaking a systematic review entails considerable work in order to achieve a good result.

The preparation of a review of the literature consists of three well-defined sequential phases, namely planning, conducting and reporting the review, that can be subsequently divided into sub-phases, as illustrated in Figure 2.1. The drafting of the review's protocol takes place in the *planning*, but concerns all phases of the systematic review, as it organizes and establishes all the methods to undertake a SR.

2.2.1 Description of phase 1: planning the review

The first step of the systematic review consists of planning, which is the foundation of the entire revision. It is at this stage that the main tools are developed, such as the Boolean function, the inclusion and exclusion criteria, the choice of the different databases in which to carry out the research and above all the development and evaluation of a protocol that regulates all the phases [38].

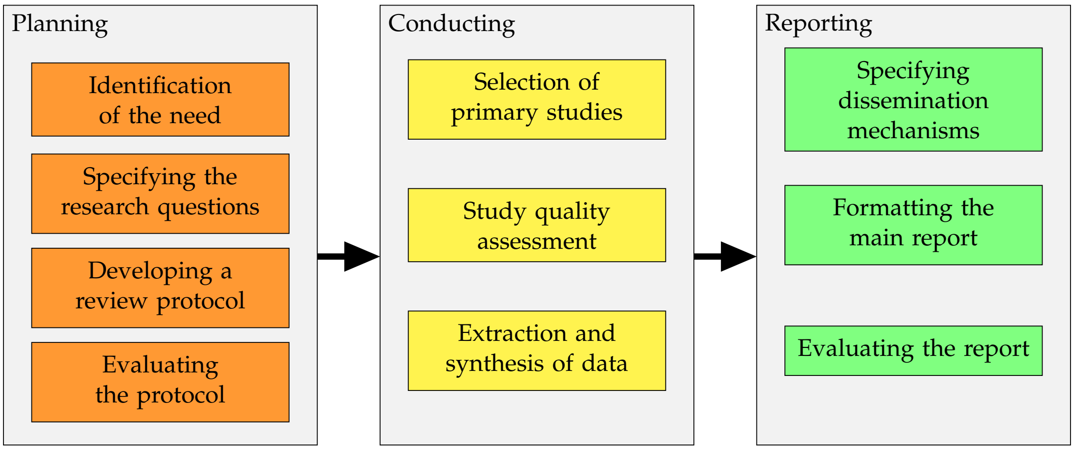


FIGURE 2.1: Phases and sub-phases of the systematic review [44]

It is divided into four actions and it begins with the identification of the need for a SR. The researchers should identify existing systematic—which are almost inexistent in our field—and traditional reviews on the topic and ensure if it is worth undertaking the review. The need to undertake a SR arises first of all because the research topic is very wide and a rigorous method was needed to correctly extract the needed information. As said, in the engineering field this type of methodology is not usual because, despite being scientific and rigorous, it is difficult and complicated to carry it out. Currently, there is no SR on the distributed estimation techniques for CPS, and in reality, there is not even a traditional revision detailed on the chosen theme.

Choosing the subject, delimiting the problem and clearly stating the research question is fundamental when conducting the SR. It is essential for the objective of the search to be consistent with the hypothesis formulated. There are some guidelines for the formulation of the research questions in the medical and psychological fields [33] or software engineering [44], there is even a battery of questions that are used to facilitate this stage, but none on automation and control. In those sectors, it is also considered the use of standard methods to frame the research questions, such as the PICOC (Population, Intervention, Comparison, Outcome, Context) criteria [68]. In the field of systems and automatic engineering, it is not obvious to formulate a collection of questions and/or criteria following the PICOC, since the areas of research are very different from each other and do not follow particular patterns. A reflection was made on how these criteria can be particularized to the automation and control sciences [41]:

Population: The target population could be very varied:

- An application area, such as solar fields, traffic systems, biological systems or smart grids.
- A particular description of a dynamical system, such as linear vs nonlinear differential equations, state-space vs transfer functions, with or without noises

or disturbances, uncertainty models, centralised vs distributed, etc.

- A well-described framework, such as fault detection, formation control, networked control systems, system identification, etc.
- A specific course, module, group of students, etc.
- A given technology or equipment, as for instance an autonomous car, a chemical plant, a robotic arm or a drone.

The population could even consist of a combination of the mentioned items.

Intervention: The intervention is the particular automation and control methodology/ algorithm/ technology that addresses a specific task. For instance, it could be a model predictive control algorithm, a methodology for modelling robotic systems or technology for performing hardware-in-the-loop simulations.

Comparison: It is the particular automation and control methodology/ algorithm/ technology that serves as comparison. For instance, distributed methodologies could be compared to centralised ones or linear controllers could be compared with standard PID controllers.

Outcome: These are factors of importance to practitioners and researchers that the proposed intervention achieves. This might be difficult to make precise, because there does not exist a normalisation of the outcomes of the studies in the control community. This drawback, which is also common for computer scientists, does not appear in social sciences, since their outcomes follow certain rules.

Some standards that usually appear in our field are: Qualitative/quantitative performance, rejection of disturbances/noises, reliability, resiliency to attacks, robustness against uncertainties in the models, computational complexity, communication needs, energy requirements or fulfilment of real-time needs.

Context: This is the context in which the comparison takes place. In this field, researchers make use of experiments or simulations to make comparisons with available interventions. Hence, some possible criteria could be: The presence/absence of a comparison, numerical vs applied simulations, field experiments, etc.

Please note that some of the previous criteria, such as outcome or context, are general and, therefore, equivalent to other fields. They were included here in order to present a self contained document. Moreover, several examples, with standard keywords, have been provided to help the potential reader in the application of this criteria to automation and control.

Once the research questions have been formulated, the next step consists in developing and, later, evaluating a protocol. The protocol mainly serves to reduce the partiality of the study, defining clearly and precociously how to conduct the entire process of the SR, with every situation and norm to be followed in each phase and sub-phase [44]. In bio-sciences, the protocol is sometimes registered in a prospective register, such as PROSPERO [1]. Unfortunately, these kinds of registers do not exist in the automation and control field.

A very important aspect to be considered for the SR is the clarity wherewith the protocol is exposed and elaborated, as at least two people are involved in the review drafting. A common, but very time consuming, approach consists in the implementation of the SR by two independent people, who carry out the part of the conducting and reporting separately and then compare and discuss the obtained results. Another method is that a person performs all the phases individually and a second person randomly checks some data.

A protocol is usually organised in three main parts, namely, introduction, methodology and a brief discussion. The introduction presents the background and context of the particular area, stating the need and aims of the review, with the research questions. The methodology should be based in a predefined standard guide, such as the PRISMA guidelines for SRs [68]. Based on those guidelines, the methodology should include, at least, the following items:

- Search strategy, that is, the key terms for the search, normally written as a Boolean function. In addition, it must be stated the sources that are going to be used to find the studies, such as digital libraries, specific journals and conference proceedings and the databases that include the contents of those sources.
- The inclusion and exclusion criteria for the studies.
- The particular procedure to be followed for the selection of primary studies. In particular, it should be mentioned the number of researchers that will evaluate the documents and the way in which a possible disagreement will be resolved.
- Assessment of risk of bias using, if possible, a standard method, such as the Cochrane guidelines [37].
- Strategy for data extraction, clearly identifying the information that is going to be gathered from the included primary studies.

It is a common practice in medicine to submit the protocol to peer review. In automation and control, it could be interesting to submit the protocol to a peer-reviewed conference with certain impact, such us the CDC, ACC, IFAC WC or ECC. This could serve as a good evaluation of the protocol. In addition and since SR are almost inexistent in automation and control, the review protocol could be evaluated by an independent expert in bio-sciences or software.

Particular features for the methodology in automation and control

[1] https://www.crd.york.ac.uk/prospero/

Some notes will be provided, concerning the methodology in the automation and control field.

Initially, the search begins by defining the Boolean function, which is nothing more than an extraction of keywords, joined by the supported operators, Booleans or not, from the different databases. It is possible also to define it as a string with the most important words and synonyms extrapolated from the initial research questions. At this point, it is worth revising several survey papers and key studies in the field to find all the possible terminology associated to the research questions.

The next step is to appropriately choose the databases best suited to the topic of investigation, making sure to get a good coverage of the most important publishers. However, the coverage of each database is sometimes, not easy to discover since the databases do not provide it in an exact way. From our point of view, in automation and control, the most important databases to be considered for a review are presented in Table 2.1. According to the information that these databases[2] put in proportion, most of the magazines and journals in automation and control and also the main conferences in this area, are published by publishers whose content appears in those databases.

Table 2.1 uses some acronyms to indicate the search fields, namely: A = abstract, T = article title, K = keywords, F = full text. The most common searches are those that cover the fields of abstracts, titles and keywords of the paper, labeled with $(A + T + K)$. Other characteristics are also included in Table 2.1, such as the number of maximum citations that can be downloaded at a single step, the format in which the citations can be downloaded, whether the downloads include the abstract or not, the Boolean operators that can be used (each database uses its own characters and Boolean operators) and the maximum number of terms allowed in the search string. Furthermore, there are two ways to perform the search in the databases: a structured advanced search (automatic) and a manual search by writing suitable commands (manual). In general, the last one let us perform more complex searches.

Another important step of the SR is the establishment of the inclusion and exclusion criteria, which are fundamental in the selection process of the papers. Each candidate study, in order to move to the next stage, must include all inclusion criteria and must not present any of the exclusion criteria.

The criteria, as indeed every step of the review, must be very clear, because the selection of primary studies is carried out, as already mentioned, by two people at the same time, who evaluate each work separately. In order to be included in the SR, the primary study must be accepted by both reviewers. In medicine or psychology, this evaluation is normally done by reading Title and Abstract. However, as it has

[2] https://webofknowledge.com/; https://dl.acm.org/; https://ieeexplore.ieee.org/; https://www.scopus.com/; https://www.sciencedirect.com/; https://link.springer.com/; https://onlinelibrary.wiley.com/; https://www.scholar.google.com/;

TABLE 2.1: Some of the most important databases in automation and control: A = abstract, T = article title, K = keywords, F = full text

Databases	Search Fields	Manual or Automatic Search	Supported Operators	N^o Terms Supported	N^o Maximum Download	Citations Format	Download with "abstract"
Web of Science	A+T+K, T, F	Both	AND, OR, NOT, NEAR, (), *, ""	Not specified	50 citations	bib, RIS, CSV	YES
IEEE Xplore	A+T+K, A, T, K, F	Both	AND, OR, NOT, NEAR, (), *, ""	Only 40	2000 citations	bib, RIS, CSV	YES
ScienceDirect	A+T+K, A, T, K, F	Both	AND, OR, AND NOT, (), *, ?, "", {}	Not specified	200 citations	bib, RIS, Text	YES
ACM Digital Library	A+T+K, A, T, K, F	Both	AND, OR, NOT, (), ""	Not specified	2000 citations	bib, RIS, CSV	NO
Scopus	A+T+K, A, T, K, F	Both	AND, OR, AND NOT, *, ?, "", ()	Not specified	2000 citations	bib, RIS, CSV, Text	YES
SpringerLink	T, F	Automatic	AND, OR, NOT, "", ()	Not specified	2000 citations	CSV	NO
Wiley Online Library	A, T, K, F	Automatic	AND, OR, NOT, "", *, ()	Not specified	20 citations	bib, RIS, Text	YES
Google Scholar	T, F	Automatic	AND, OR, NOT, "", ()	Not specified	1 citation	bib, RIS	NO

been discovered by conducting this SR, titles an abstract in automation and control and other engineering fields are seldom normalised and, unluckily, sometimes they do not contain the necessary information to perform the evaluation. In those cases, the reviewer must read the full text. In the case of disagreement, a third person will decide whether to include it or not. This is a well-extended practice in SRs that it helps to preserve neutrality .

The last points to consider are the study quality assessment checklist and the data extraction strategy. As it has already been seen with other aspects of the SR, there does not exist a quality checklist to assess the individual studies in our field, so the reviewers could opt between modifying and adapt those found in the bio-science/social science literature or discarding this step.

Finally, for the data extraction, the following list of items is suggested. When extracting the data from the selected papers, among the characteristics that could be extracted, in general there are:

- basic information: authors, year of publication, title, etc;

- field of application or study subjects or study type of each paper;
- particular information related to the application context;
- tools used;
- test/experiment/simulation;
- limitations and advantages.

2.2.2 Description of phase 2: conducting the review

Once the precise research questions have been established, the appropriate databases have been chosen, the Boolean function has been defined and the inclusion and exclusion criteria have been set, it is possible to move on to the second block of the SR, which basically includes the selection of primary studies, study quality assessment, extraction and synthesis of data.

In order to guide this process, an international group of experts has developed the PRISMA method: a framework for the realisation of a SR [68], which consists of 27 points and a flow diagram (see Section 2.3) that summarises the selection process.

At this point, the reviewers have to deal with a considerable quantity of data coming from the different databases used. The first filter, which is often included directly in the database, is the elimination of gray literature, which includes books, book chapters, poster presentations, reviews, surveys and doctoral theses that usually gave rise to a journal article. In conclusion, it will be included only original works that have gone through a peer-review process. It is of a crucial importance to use a tool to eliminate the duplicates, since the databases in automation and control share part of their content.

Then, the obtained primary studies will be evaluated by the reviewers (normally two, as explained before) following the predefined protocol and applying the inclusion and exclusion criteria. This step will provide the list of selected primary studies to be included in the SR.

In order to improve the list of studies, it is a good practice at this stage to contact the authors of the selected papers and check their bibliography to see if any possible paper has escaped the initial search. These additional papers will be included in the list of selected primary studies under the name of additional records identified through other sources (see Figure 2.2). In the event that many items were found that were not included in the first list of studies, it is advisable to restart the SR, following the PRISMA procedure again.

The quality of the different works is evaluated using the tool presented in this subsection. For this work, it has been developed a very simple checklist that can be used to assess the quality of the papers included in the SR, see Table 2.2.

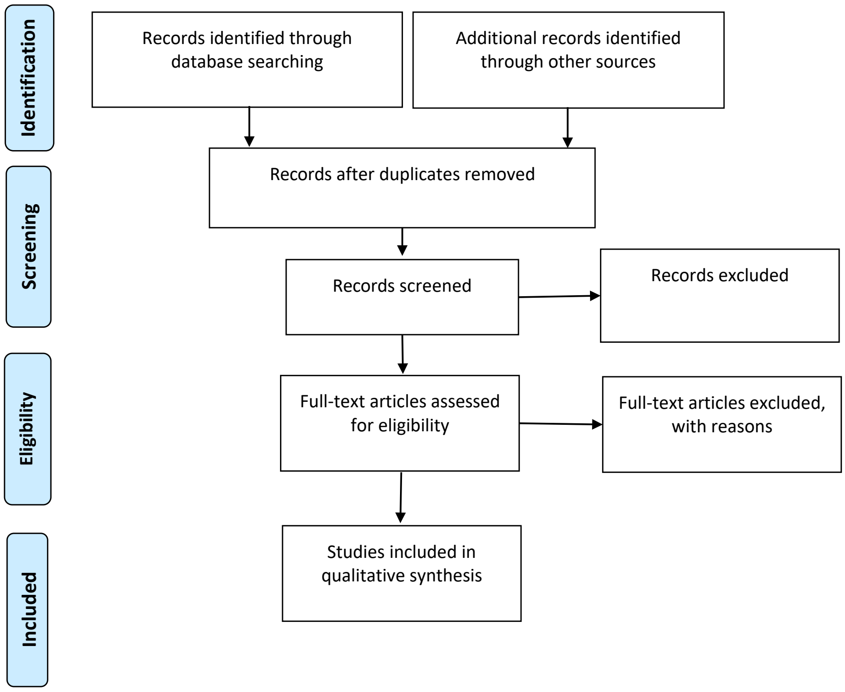


FIGURE 2.2: PRISMA flowchart

TABLE 2.2: Checklist for quality assessment [41]

	Question	Score
Q1	Is the problem presented clearly?	Yes/Partially/No
Q2	Is the methodology used presented clearly?	Yes/Partially/No
Q3	Are there any limitations and/or restrictions?	Hard/Soft/No
Q4	Is there a discussion of the results?	Yes/Partially/No
Q5	Does it answer all the questions originally formulated by the SR?	Yes/Partially/No
Q6	Has it been cited by many authors?	Cites/Year
Q7	Has it been published in a journal or conference proceeding?	Journal/Conference

For the extraction and synthesis of the data of each selected paper one can resort to different ways to re-organise the information, such as a narrative synthesis, a concept map or a table of characteristics. The latter is, perhaps, more useful in automation and control, since the reader (practitioner or researcher) will easily see the information collected from the studies and will be able to extract his/her own conclusions. These tables, in addition to standard information such as authors and year of publication, present the information that has been previously stated in the protocol. They summarise in a visual way the features and peculiarities of each work.

The data extraction procedure should be performed by more than one reviewer, following a similar protocol than the one established for the inclusion of primary studies. If this cannot be done, at least, some methods should be introduced to check that the data are being extracted correctly. For instance, if a PhD is conducting this phase, the supervisor could randomly pick some of the studies and extract the features, to make a comparison with the data extracted by the student. In general, the risk of bias or rigorousness can be reduced by including more people in any decision.

2.2.3 Description of phase 3: reporting the review

The conclusive part of the SR concerns the preparation, reporting and dissemination of all the results obtained, that is the documentation of the extracted data. A critical and objective analysis of the salient features of the works must be presented, comparing the obtained results and reasoning on them.

In order to disseminate the results, there are different options, which should be taken into account depending the target audience: academic journals/conferences, practitioner-oriented magazines, posters, web pages or direct communication. The choice of the dissemination mechanism directly affects the format in which the SR will be reported. The structure and contents of this report are usually normalised in other areas [44].

The evaluation of the report will be done as an unavoidable step when it is submitted for publication to a peer-reviewed journal.

2.3 Report of the systematic review

This section presents the report of the systematic review on distributed estimation techniques applied to cyber-physical systems, that follows the structure previously presented.

2.3.1 Background

For the distributed estimation of the state on sensor networks there are various algorithms proposed in the literature that constitute extension of well-known classical estimators.

The first family of techniques, referred to as Kalman filters, uses a series of measurements observed over time, containing statistical noise and other uncertainties to identify the hidden state, not measurable [42]. In particular, the Kalman filter operates by propagating the mean and covariance of the state through time. In the last decades, it has been applied to distributed systems with great success, see for instance [17], [18], [73].

Another approach to state estimation is the Bayesian filter, which produces recursively an estimate for the targets joint probability density, given the current information [89]. It is a statistical approach to estimate, in particular for the systems that are highly nonlinear. It is a probability-based estimator [88]. Some extensions to distributed frameworks in combination with particle filters can be found in [11], [78], [84].

An additional noteworthy estimation technique is the Luenberger observer. It estimates the hidden internal state not measurable of a linear dynamic system from the measurements of the input and output of the system [56]. Recently, many authors have proposed different formulations of distributed Luenberger observers [47], [64], [66].

Further techniques exist and have found application for distributed plants. For instance, adaptive observers model the relationship between signals in real time in an iterative way, changing their coefficients according to an adaptive algorithm [15]. H_∞ filters [88] are mainly used for multi-variable systems with couplings between the channels and with systems that have model uncertainty, see [91]. Sliding mode observers, with important measurement noise resilience, have been applied in [100]. Finally, set-membership observers are mainly used when noises and disturbances are bounded, in such a way that no statistical description is required, see [76].

2.3.2 Review Questions

The goal of this SR consists in locate and compare the different distributed estimation techniques that have been applied to cyber-physical systems. In pursuing this goal, the next research questions have been formulated:

RQ.1: What distributed estimation techniques are used in cyber-physical systems, heterogeneous systems or system of systems?

RQ.2: What are the limitations and advantages of the different techniques?

RQ.3: What are the fields of application in which these techniques are used?

RQ.3.1: In applications that include humans, animals or biological systems, which estimator obtains better results?

Since the term cyber-physical systems is kind of new, the more general terms heterogeneous systems and system of systems were included, which sometimes are used to refer to a CPS. Using the proposed PICOC criteria defined in Subsection 2.2.1, these research questions are described by:

- Population: Cyber-physical systems, heterogeneous systems or system of systems.
- Intervention: Distributed estimation.
- Comparison: No additional criterion.
- Outcome: Type of design (decentralised/centralised), exchanged information, communication protocol, another advantage/disadvantage.
- Context: No additional criterion.

It was left the "comparison" and "context" criteria empty in order to not further restrict the search and so that more candidates papers are screened.

2.3.3 Review Protocol

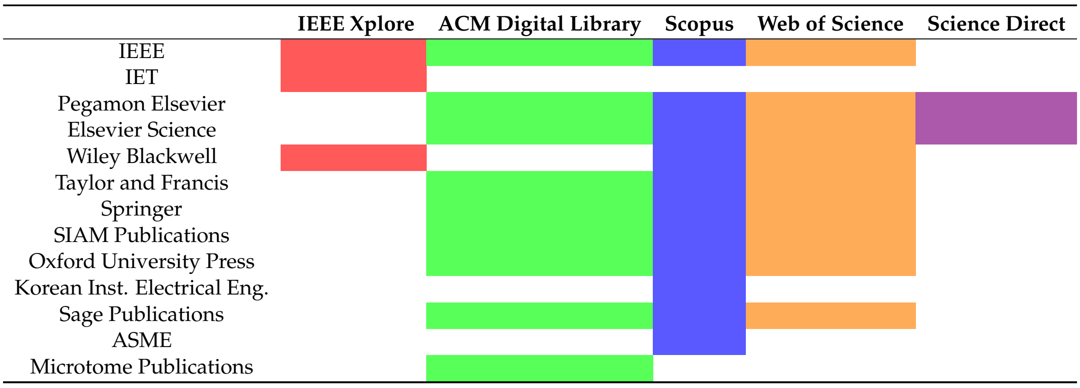
The review protocol, as already mentioned in Subsection 2.2.1, is nothing more than a set of rules and criteria to be followed during all the stages, in order to reduce the bias and make the SR as objective as possible.

2.3.3.1 Data Sources and Search Strategy

The databases presented in Table 2.3 were chosen, namely, IEEE Xplore Digital Library, Web of Science, ScienceDirect, ACM Digital Library and Scopus. The reason for this choice is twofold. Firstly, those databases that did not allow to make the search in the abstract, title and keywords were excluded, as detailed in Table 2.1. Secondly, the content of these databases covers the main publishers in automation and control, as Table 2.3 illustrates in a graphical way.

The time interval considered for the search goes from 01/01/1990 to 12/09/2019.

TABLE 2.3: Databases coverage with respect to the content of the publishers [38]



The articulate Boolean function created for this SR is as follows:

> (Estimator OR Estimation OR Filter OR Filtering OR Observer OR Observability OR Sensing) AND
>
> ("Cyber Physical System" OR "Human in the loop" OR "Human Robot" OR "System of systems" OR "Heterogeneous System" OR "Human Machine" OR "Heterogeneous Multiagent System" OR "Humanoid Robot" OR "Animal Robot" "Biological System" "Physical System" "Physically-aware Engineered Systems") AND
>
> (Distributed OR Decentralised OR Decentralized OR "Sensor Fusion" OR "Multi Sensor")

The first and third block refers to the *Intervention*. Note that similar terms must be included if we want to be sure that all the studies proposing distributed estimation techniques are going to be considered. The reader may find strange that the terms decentralized/decentralised or Sensor fusion appear in the search string when the proposed research questions clearly avoid them. The reason is that it was discovered that some authors use those names when they are proposing a distributed estimation technique.

With respect to the *Population*, the second block includes a set of key terms that are found in the literature for applications similar to those in which the SR is interested. These terms have been found by reading some survey papers in the field, with my expertise and that of my supervisors, by several post refinements after making trial searches.

2.3.3.2 Study Selection

The guidelines presented in the protocol (Subsection 2.2.1) have been followed. Two reviewers evaluate each work separately and, to be included, the primary study must be accepted by both reviewers, leaving to a third reviewer the final decision in case of disagreement. The PRISMA method [68] was used to drive this sub-phase.

In the screening step, the inclusion and exclusion criteria are applied to the title and abstract. Then, a full text reading will be executed on the preliminary candidate studies to finally discard those studies that did not satisfy all the inclusion criteria.

2.3.3.3 Study Quality Assessment

In this section the checklist for quality assessment is applied. This is shown in the Table 2.2 for the papers selected for the SR, to highlight the quality through the different questions.

2.3.3.4 Data Extraction and Synthesis

This SR will summarise the extracted data from the selected primary studies using a feature table. The data that will be extracted from the selected papers and included in the tables are:

- Year of publication.
- The sort of estimator used, such as a Kalman filter, a Luenberger observer, a Bayesian filter or any other.
- The application, that is, what kind of dynamical system the estimator has been applied to, such as biological systems, structural health monitoring, CPS under some kind of cyber-attack and so on.

- The inclusion of simulations and/or field experiments that demonstrate the effectiveness of the used estimator.
- The estimation objective, which indicates whether the dynamics to be estimated corresponds to the whole state vector or just a partial state vector associated with a local dynamics of each subsystem.
- The design of the proposed estimator, whether it is made in a centralised or a decentralised way, considering that the implementation must be decentralised.
- The information that needs to be exchanged between the agents. Two aspects are mentioned here: The size of the packets to be transmitted (using state vector (n) and output or sub-component of the state (r) as a reference); the frequency at which those packets must be sent, distinguishing between those estimators that require consensus steps between two consecutive sampling times and those estimators that run at the same rate as the plant.
- The communication protocol. This work is not interested in the particular protocol, such as WiFi or ZigBee, but on the way each agent relates with the others. In particular, it will be annotated whether the estimation algorithm requires all-to-all communication or just communication with neighbouring agents. While there are other options, such as gossip or scheduled communication, no primary studies have been found to suit those categories.
- Other advantages/limitations that the authors of the primary studies mention or the reviewers discover. This feature is the only one that is subjective. However, information that is not collected in the other features can be added at this point.

The data will be extracted by two reviewers to reduce the bias, going for a third one in case of disagreement. For the last features, both reviewers must agree on the selected advantage/limitation.

2.3.4 Included and Excluded Studies

The inclusion and exclusion criteria chosen for the selection of papers are shown in Tables 2.4 and 2.5, respectively.

The selected criteria ensure that the search is focused on the chosen topic. For a paper to be included, it must satisfy all the inclusion criteria and none of the exclusion criteria. As mentioned in the introduction, the interest of this work is based on those heterogeneous systems that have a certain dynamic and that incorporate a physical and a cybernetic part. Furthermore, the estimators must interchange some form of information with other agents.

TABLE 2.4: Inclusion criteria

- Full paper available online (through search engines or by contacting the authors)
- Use or propose a distributed estimation technique on cyber-physical systems, heterogeneous systems or system of systems or make specific reference to humans, animals or biological systems
- Use a distributed estimator with some sort of communication between local estimators
- The system to be estimated must have dynamics

TABLE 2.5: Exclusion criteria

- Secondary studies and gray literature
- Non-English written papers
- Duplicated studies
- Studies clearly irrelevant to the research
- Focused only on control

The number of papers obtained by launching this Boolean function in the chosen databases were 2848, see Table 2.6. The PRISMA complete flowchart is shown in Figure 2.3.

TABLE 2.6: Studies obtained by each database

Database	Studies
Web of Science (WoS)	571
IEEE Xplore (IEEEX)	919
ScienceDirect (SD)	51
ACM Digital Library (ACM)	525
Scopus	782
	2848

In this flowchart, in addition to the studies found in the aforementioned databases, those identified through other sources are specified, for example by contacting the authors and revising the bibliography of the selected papers. At this point the duplicates are removed, which are more than 1000 for our particular case, using an appropriate reference manager, such as Mendeley.

After the screening phase, the remaining studies are far less than the large quantity that occurred at the beginning: from the initial 2848 works, 102 papers remains.

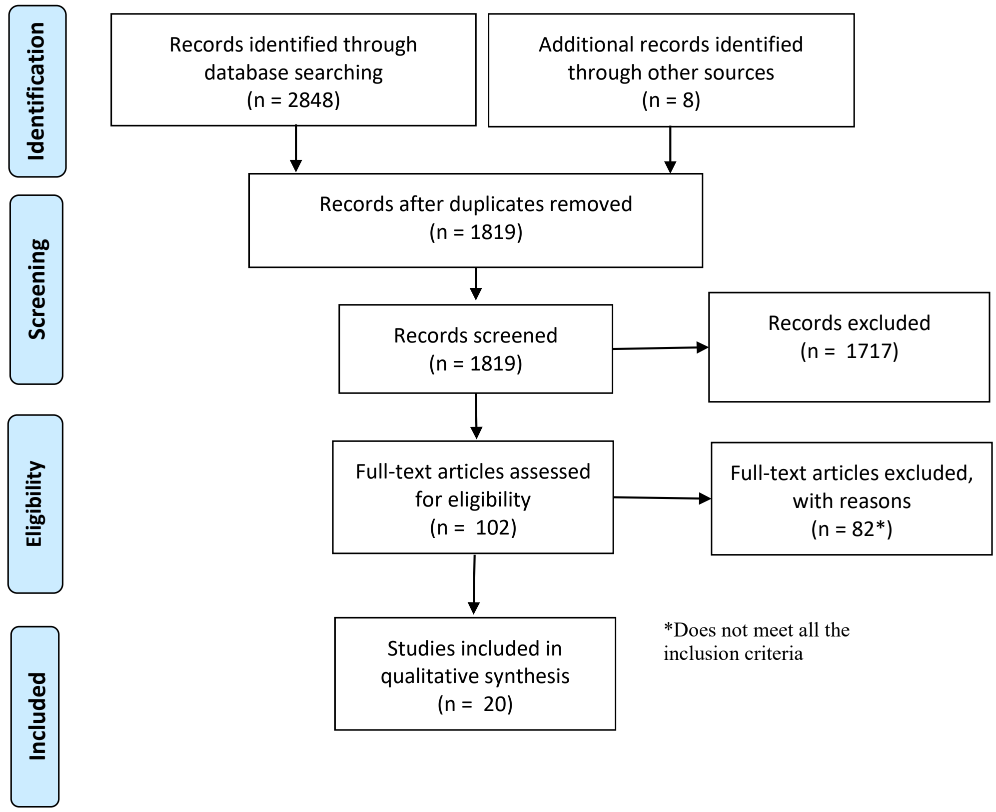


FIGURE 2.3: Adapted PRISMA flowchart

However, after a full-text reading, 82 papers were discarded. Finally, 20 papers have been found, a much smaller amount if compared to the initial 2848, as shown in Figure 2.4. In spite of the low percentage of selected papers, the analysis of these 20 papers indicates that they were an enough number of documents to identify interesting research gaps and conclusions.

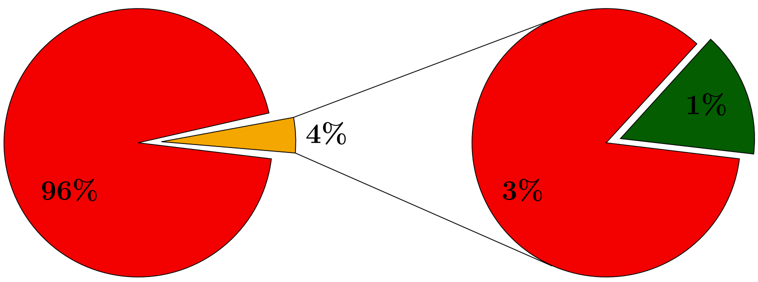


FIGURE 2.4: Paper inclusion statistics

2.3.5 Results

The quality of the selected papers have been assessed, obtaining the results depicted in Table 2.7.

The data extracted from the papers have been included in different tables, namely Tables 2.8–2.11, each associated to a research question. In the following section, the data are analysed and several conclusions are drawn.

TABLE 2.7: Quality assessment of the results

	Q1	Q2	Q3	Q4	Q5	Q6	Q7
[13]	Yes	Yes	No	Yes	Partially	27/2008	Conference
[90]	Yes	Partially	Soft	No	Yes	2/2010	Conference
[82]	Yes	Yes	Soft	Yes	Yes	1/2012	Journal
[60]	Yes	Partially	Soft	Partially	Yes	24/2012	Conference
[45]	Yes	Partially	Soft	Yes	Yes	17/2013	Conference
[59]	Yes	No	No	Yes	Yes	5/2013	Conference
[83]	Yes	Yes	No	Yes	Yes	46/2014	Journal
[21]	Yes	Yes	Soft	Yes	Yes	81/2015	Journal
[8]	Yes	Yes	Hard	Partially	Yes	3/2016	Conference
[25]	Yes	Yes	Hard	No	Yes	9/2016	Conference
[26]	Yes	Yes	Soft	Partially	Yes	5/2016	Conference
[65]	Yes	Yes	Soft	Partially	Yes	25/2016	Conference
[67]	Yes	Yes	Soft	Yes	Yes	47/2016	Journal
[2]	Yes	Partially	Soft	Partially	Yes	2/2017	Conference
[7]	Yes	Yes	Soft	Partially	Yes	1/2017	Conference
[28]	Yes	Yes	No	Yes	Yes	14/2018	Journal
[34]	Yes	Yes	Hard	Yes	Yes	38/2018	Journal
[9]	Yes	Yes	Soft	Yes	Yes	1/2018	Journal
[69]	Yes	Yes	No	Yes	Yes	1/2018	Conference
[96]	Yes	Yes	Soft	Yes	Yes	13/2018	Journal

2.4 Discussion

The SR is completed by carrying out the discussion. Firstly, the principal findings will be clarified and, later, an analysis on the strengths and weaknesses of the SR will be performed.

2.4.1 Principal Findings

In the following, it will be provide a clear and detailed answer to each of the research questions that were exposed at the beginning of the review.

RQ.1: What distributed estimation techniques are used in cyber-physical systems, heterogeneous systems or system of systems?

The distributed estimation techniques used in the selected papers are varied, as Table 2.8 shows. In this view it is interesting to see how the number of papers based on certain techniques according to the year of publication is distributed and with what percentage fee they are presented. (Figures 2.5 and 2.6).

Mainly they can be divided into the following groups:

- Adaptive observer, used in [26] for multi-agent systems, in [67] for leader–follower systems and in [96] for heterogeneous multi-agent system.

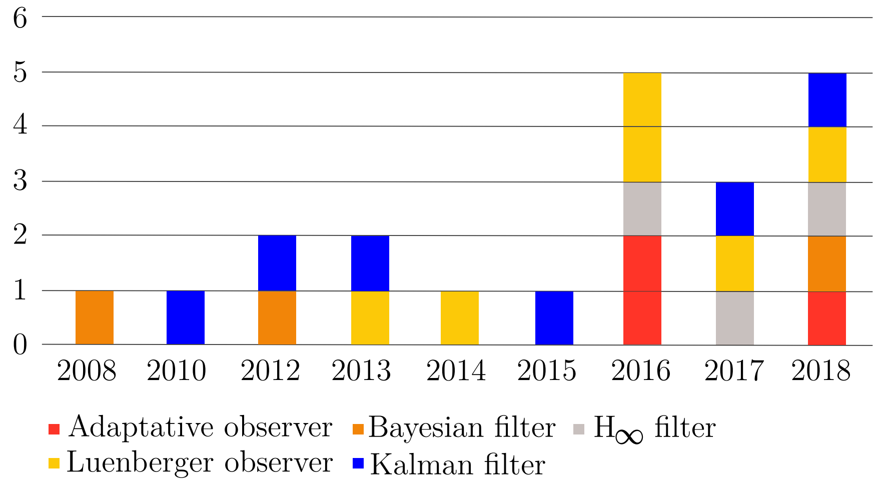


FIGURE 2.5: Distribution of the used techniques over the publication year

- Bayesian filter, also used in many areas, such as collaborative human–robot systems [13], joint attack detection and secure state estimation [28] or 3D upper body tracking, with a combination of annealing particle filter and belief propagation inference [82].
- H_∞ filter, which has been applied for the detection of biasing attacks on distributed estimation networks [25] and for the joint attack detection and secure state estimation [34].
- Luenberger observer, used in [45] for CPSs affected by adversarial attacks on the sensed and communicated information, in [83] for detecting and isolating multiple sensor faults, in [8] for the simultaneous estimation of the state and attack, in [9] with a secure pre-selector, in [65] for the state estimation in networks subject to adversarial attacks.
- Kalman filter, which has been used in various fields of application, such as fault detection and isolation for systems of systems [90], security of the state estimation in power systems [60], for attack detection in [69], multi-robot tracking [59], monitoring industrial CPSs [21] or estimation of the biofilm growing process in a biological system [7].

It should be mentioned the paper [2], which presents two different estimation techniques: the attack estimation is carried out by means of a H_∞ filter, whereas the state estimation, considering the attack previously estimated, is done with a Luenberger observer.

Finally, it deserves to be remarked that some estimators have not been found to be applied to CPSs, such as sliding mode observers or set-membership observers.

RQ.2: What are the limitations and advantages of the different techniques presented in the different papers?

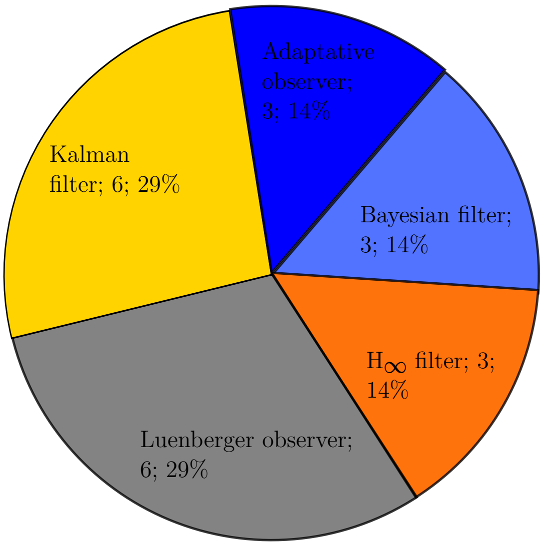


FIGURE 2.6: Distribution of the papers according to the used techniques

TABLE 2.8: Feature table. Estimation technique and application

Cite	Year	Estimator Used	Application
[26]	2016	Adaptive observer	Heterogeneous multi-agent system
[67]	2016	Adaptive observer	Heterogeneous multi-agent system
[96]	2018	Adaptive observer	Heterogeneous multi-agent system
[13]	2008	Bayesian filter	Heterogeneous multi-agent system
[28]	2017	Bayesian filter	Attack detection and secure estimation
[82]	2012	Particle filter + Belief Propagation inference	3D Upper body pose estimation
[34]	2017	H_∞ filter	Attack detection and secure estimation
[25]	2016	H_∞ filter	Attack detection
[2]	2017	Luenberger observer and H_∞ filter	Attack detection
[45]	2013	Luenberger observer	Secure estimation
[65]	2016	Luenberger observer	Secure estimation
[83]	2014	Luenberger observer	Fault detection and isolation
[8]	2016	Luenberger observer	Attack detection and secure estimation
[9]	2018	Luenberger observer with secure pre-selector	Attack detection and secure estimation
[90]	2010	Kalman filter	Fault detection and isolation
[60]	2012	Kalman filter	Secure estimation
[59]	2013	Kalman filter	Heterogeneous multi-agent system
[21]	2015	Kalman filter	Monitoring industrial CPSs
[7]	2017	Kalman filter	Biological system
[69]	2018	Kalman filter	Attack detection

This question is focused on the limitations and/or advantages that have been found in the selected papers and shown in the Table 2.9. The answer to this question is rather complex and wide, because, when studying a paper, it is not easy to extract the limitations and/or advantages, because it is sometimes a subjective aspect. In the following, some reflections and considerations extracted from the data will be presented below.

First, we pay attention to the design of the estimators. Whereas most of the studies present design methods that can be implemented in a decentralised way, there are some papers in which the estimators need to be design in a unique centralised step. This is the case of [25], [34], where a unique linear matrix inequality (LMI) must be solved to find the observer gains. In [8] the authors require to solve decentralised Lyapunov matrix equations to ensure that both the state and the attack is estimated. However, those equations require global information that, in general, is not available in every location, such as the output matrices and Luenberger observer gains of every estimator.

It is worth mentioning that most authors have used H_∞ filters for attack detection, see [2], [25], [34]. In order to ensure a given H_∞ bound γ, all these papers require to solve centralised LMIs. In fact, there exists no study that has solved this problem using a pure decentralised approach. Other options available are the papers [8], [28]. The former, based on a Luenberger observer, is adequate when the system is described as a set of, possibly nonlinear, subsystems. The latter uses a Bayesian filter to estimate the complete state of the plant.

Consensus algorithms have been vastly used in distributed estimation in general and in distributed estimation for CPSs in particular, see [2], [7], [13], [21], [25], [28], [34], [45], [60], [65], [90]. While the consensus methods are well known, it should be remarked that there are important differences in the way they influence the estimation algorithm. Mainly, it could distinguish between those consensus iterations that run at the same rate of the estimator [13], [25], [34], [45], [65], [90] and those others that need to be executed many times (usually a large number of iterations, since consensus algorithms typically converge asymptotically) between two consecutive estimation steps [2], [7], [21], [28], [60]. Therefore, and despite the same word being used in the papers, enormous differences exist in what respect the information exchanged (see Table 2.10).

Consensus algorithms are used in those papers with several objectives. The most common application is for the agreement in the estimated state vector, see [25], [34], [45], [60], [65], [90]. Another example is found in [2], where consensus is used for the residuals. The authors in [7], [21] use the consensus because they need to estimate the output vector. Finally, the approaches in [13], [28] incorporates a consensus algorithm to achieve an agreement in a probability density function.

Concerning the consensus gains that those algorithms use, in the vast majority of cases it consists in a scalar gain, as for example in [26], [28], [45], [65], [67], [96]. In [90], a consensus matrix is proposed, but it is required to be diagonal matrix.

TABLE 2.9: Features table. Limitations and advantages according to a given criteria. Color code: Green = desired, yellow = intermediate, red = undesired.

Cite	Estimator Used	Experiment or Simulation	Estimation Objective	Design	Exchanged Information	Communication Protocol
[26]	Adaptive observer	Simulation	Local state	Decentralised	Estimated state vector (n) + adaptive system matrix (n*n), same rate as the system	Neighbourhood
[67]	Adaptive observer	Simulation	Local state	Decentralised	Estimated state vector (n) + adaptive system matrix (n*n), same rate as the system	Neighbourhood
[96]	Adaptive observer	Simulation	Local state	Decentralised	Estimated state vector(n) + adaptive system matrix (n*n), same rate as the system	Neighbourhood
[13]	Bayesian filtering	Experiment	Complete state	Decentralised	Estimated state vector (n) and output (r<n), same rate as the system	Neighbourhood
[28]	Bayesian filter	Simulation	Complete state	Decentralised	Estimated state vector (n) consensus between sampling instants	Neighbourhood
[82]	Particle filter + Belief Propagation inference	Experiment	Local state	Decentralised	Estimated state vector (n) * Number of particles (N), at a rate N_{BP} higher than the rate of the system	Neighbourhood
[34]	H_∞ filter	Simulation	Complete state	Centralised	Estimated state vector (n), same rate as the system	Neighbourhood
[25]	H_∞ filter	None	Complete state	Centralised	Estimated state vector (n), same rate as the system	Neighbourhood
[2]	Luenberger observer and H_∞ filter	Simulation	Local state	Decentralised	Estimated state vector (n), consensus between sampling instants	Neighbourhood
[45]	Luenberger observer	Simulation	Complete state	Decentralised	Estimated state vector (n) and output (r<n), same rate as the system	Neighbourhood

TABLE 2.9: *Cont.*

Cite	Estimator Used	Experiment or Simulation	Estimation Objective	Design	Exchanged Information	Communication Protocol
[65]	Luenberger observer	None	Complete state	Decentralised	Estimated state vector (n), same rate as the system	Neighbourhood
[83]	Luenberger observer	Simulation	Local state	Decentralised	Subset of the estimated state vector (r<n), same rate as the system	Neighbourhood
[8]	Luenberger observer	Simulation	Local state	Centralised	Estimated state vector (n), same rate as the system	All-to-all
[9]	Luenberger observer with a secure pre-selector	Simulation	Local state	Decentralised	Estimated state vector (n), same rate as the system	All-to-all
[90]	Kalman filter	Simulation	Complete state	Decentralised	Estimated state vector (n) and residuals (n), same rate as the system	All-to-all
[60]	Kalman filter	Simulation	Complete state	Decentralised	Estimated state vector (n), consensus between sampling instants	Neighbourhood
[59]	Kalman filter	Both	Local state	Decentralised	Estimated state vector (n), same rate as the system	All-to-all
[21]	Kalman filter	Simulation	Complete state	Decentralised	Estimated state vector (n), same rate as the system + augmented output vector (n) and augmented noise matrix (n*n), tree-based broadcasting + augmented output vector	Neighbourhood
[7]	Kalman filter	Simulation	Complete state	Decentralised	Estimated state vector (n), consensus between sampling instants	Neighbourhood
[69]	Kalman filter	Simulation	Local state	Decentralised	Estimated state vector (n) same rate as the system	Neighbourhood

TABLE 2.10: Features table. Other limitations and advantages

Cite	Estimator Used	Limitations	Advantages
[26]	Adaptive observer	Scalar gains. Measure the whole state	Do not require to know the system matrix. The consensus gains are dynamically chosen
[67]	Adaptive observer	Scalar gains.	Do not require to know the system matrix
[96]	Adaptive observer	Scalar gains. Leader's dynamics is required	Do not require to know the system matrix
[13]	Bayesian filter	Acyclic communication graphs	Moving sensors and targets. Collaboration between human and robots. Consider packet dropouts
[28]	Bayesian filter	Secure communication between fusion nodes. Scalar consensus gains	Nonlinear systems. Different kinds of attacks
[82]	Particle filter + Belief Propagation inference	Communication effort	Linear complexity according to the number of body parts
[34]	H_∞ filter	LMI centralised design. Require statistical information	Different kinds of attacks.
[25]	H_∞ filter	LMI centralised design	Local and consensus matrix gains Attacks on the estimator dynamics
[2]	Luenberger observer and H_∞ filter	No method for design the observer gains. Centralised detection based on H_∞ filter. Communication effort	Descriptor system. Attack policy on sensor signals
[45]	Luenberger observer	Direct state observations. Full rank output matrix. Scalar consensus gains	Robust against compromised communication
[65]	Luenberger observer	Constraints in the system matrix. Scalar consensus gains	Decoupling of observable and unobserval dynamics. Byzantine adversaries
[83]	Luenberger observer	Fusion centre for fault isolation	Observer for Lipschitz nonlinear systems. Multiple fault detection and isolation. Structured fault sensitivity
[8]	Luenberger observer	Global information for design	Nonlinear descriptor systems. Neural network for uncertainty approximation
[9]	Luenberger observer with a secure pre-selector	Only out of sensors are manipulated arbitrarily by attackers	the exact secure state estimation is achieved in a pregiven finite time
[90]	Kalman filter	The consensus matrix gains are diagonal. There is no algorithm to design these gains	Distributed decision make without fusion center.
[60]	Kalman filter	Communication effort. Consensus constraints as in Olfati Saber[73]	Robust against false data injection
[59]	Kalman filter	The estimator is not presented formally	Moving sensors. Low computational requirements
[21]	Kalman filter	Communication effort	Two kinds of nodes: sensor and relay nodes
[7]	Kalman filter	Mono-variable system. Requires statistical information of the graph. Communication effort	Consensus under interferences, packet losses and different topologies
[69]	Kalman filter	Communication effort	There are no restrictions on the types of attacks

Only the paper [25] uses a consensus matrix, but it is a unique matrix gain for every neighbour and it must be found after an LMI. Hence, it has been observed that none of the proposed studies have been able to use (and distributed design) different consensus gains for every neighbour.

To deepen the discussion concerning the required communication (see Table 2.10), it is noted that in those estimators based on the Luenberger observer, i.e. [8], [9], [45], [65], [83], the information exchange between agents takes place at the same rate as the estimation algorithm. Moreover, the agents exchange the estimated state vector or a sub component of it. On the contrary, those approaches based on Kalman filters usually require a lot of information, as in [21], or consensus iterations between estimation steps, as in [7], [60], with the consequent communication effort. A similar drawback appears in [82], where a lot of information must be sent between the particles of the filter between two consecutive sampling instants.

Distributed estimation techniques have been also applied to fault detection and isolation, see [83], [90]. Both studies present distributed fault detection algorithms, for LTI systems [90] and for Lipschitz nonlinear systems [83]. It should be noted that, whereas in [83] a fusion centre is required for fault isolation, the algorithm presented in [90] is able to provide distributed decisions.

Finally, it is worth mentioning the research developed in [13], [59] for heterogeneous multi-agent systems. These studies consider a group of robots that are endowed, among others, with an estimation unit. These units have the objective of estimating the state (position, velocity orientation) of the associated robot and some target (a ball position, as in [59] and other robots' states, as in [13]). The presented estimation algorithms can be implemented in moving agents.

RQ.3: What are the fields of application in which these techniques are used?

Most of the applications found in the selected papers lie within the following four main categories (see Table 2.11 and Figure 2.7):

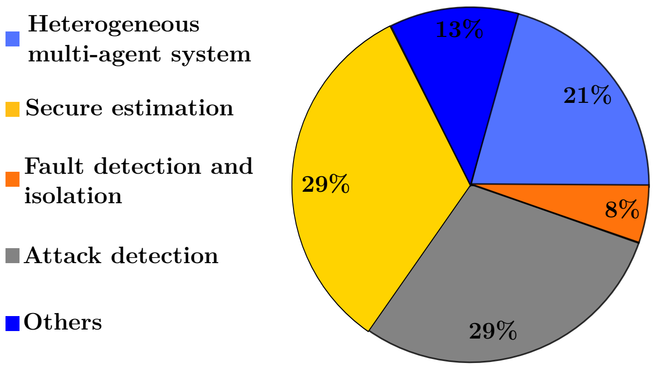


FIGURE 2.7: Fields of application in which the techniques are used

- Heterogeneous multi-agent system: different cases are considered in these studies in which there are different types of systems. In [13] a scalable collaborative human–robot system for information gathering applications, through a decentralized Bayesian fusion algorithm, is presented. The results of a collaborative multi-target search experiment conducted with a team of four autonomous mobile sensor platforms and five humans carrying small portable computers with wireless communication are presented to demonstrate the efficiency of the approach. In the paper [59], a multi-object, multi-sensor and cooperative tracking method using a Kalman filter is proposed for the Robocup Standard Platform League, where two teams of humanoid robots play soccer against each other.

It is worth mentioning that the documents [26], [67], [96] deal with the same application, that is, the synchronization of heterogeneous systems. All those papers propose the use of an adaptive observer, with different modifications, as will be mentioned next.

The exogenous signal representing the reference input to be tracked is assumed to be generated by a so-called exosystem as follows:

$$\dot{x}_0(t) = S_0 x_0(t), \tag{2.1}$$

with S_0 being a known constant matrix.

The agents are modelled as linear time-invariant systems described by:

$$\begin{aligned} \dot{x}_i(t) &= A_i x_i(t) + B_i u_i(t) + E_{xi} x_0(t) + E_{wi} w_i(t), \\ y_{mi}(t) &= C_{mi} x_i(t) + D_{mi} u_i(t) + F_{m_{xi}} x_0(t) + F_{m_{wi}} w_i(t), \end{aligned} \tag{2.2}$$

where for $i = 1, \ldots, N$, x_i, y_{mi}, u_i are the state, measurement output and input of the ith subsystem. External disturbances w_i are assumed to be generated by an independent linear system, that is, $\dot{w}_i(t) = Q_i w_i(t)$.

The authors in [26] propose a self-tuning observer to estimate the state of the leader from each agent. Then, using this information, they compute appropriate control inputs to achieve the synchronization between the states of the leader and followers.

The main novelty of [67] is that both the leader's and the follower's dynamics are assumed to be unknown. On the other hand, the synchronization problem is posed in [96] as a distributed optimal tracking problem, deriving inhomogeneous algebraic Riccati equations to solve it.

- Attack detection and secure estimation: Intense research has been done in these categories, with some papers tackling both challenges at the same time. They represent most of the applications encountered, even if in some papers it is only the attack detection, like in [2], [25], [69] and in others only the secure estimation, like in [45], [60], [65]. Only in [8], [9], [28], [34] are both considered. Secure estimation is certainly among the most addressed topics in the reviewed articles. Perhaps the main difference between those papers is the typology of the attacks/attackers and the way the secure estimation is achieved.

False data injection attack: this happens when a malicious adversary launches false data injection attacks at the physical system layer to intentionally modify the system's state and/or the measured output. From a mathematical point of view, false data injection attacks are usually modeled as additive disturbance or additive noise:

$$x^+ = \begin{cases} f_1(x,u,w), & \text{Under no attack} \\ f_2(x,u,w,a), & \text{Under attack} \end{cases}, \quad y = \begin{cases} h_1(x,v), & \text{Under no attack} \\ h_2(x,v,b), & \text{Under attack} \end{cases}, \tag{2.3}$$

with x, u, w, v being the state, input, external disturbance and measurement noise, respectively, and a, b the false data injection in the system dynamics or the measured output.

This is the case in [8], in which the attacks affects both the dynamics of a nonlinear descriptor system and the measurement output. This paper proposes a distributed robust approach using a Luenberger observer. Similarly, in [28], the attack detection-state estimation problem is formulated in the context of random set theory by representing the joint information on the attack presence/absence, on the system state and on the signal attack, in terms of a hybrid Bernoulli random set density, using a recursive Bayesian filter.

Several authors consider a simplification of the previous problem by assuming a linear time-invariant system, such as:

$$\begin{aligned} x(k+1) &= Ax(k) + Bu(k) + B_w w(k) + Ea(k), \\ y(k) &= Cx(k) + v(k) + b(k), \end{aligned} \tag{2.4}$$

where $x(k), u(k), y(k), w(k), v(k)$ are, respectively, the state, input, the measurement output, disturbances and the process noise at the k-th time step. The attack signals are $a(k), b(k)$.

In this line, [34] studies the situation in which the attacks only affects the system dynamics (i.e., $b(k) \equiv 0$). They propose an distributed H_∞ filter for attack detection and secure estimation. The attacks on the outputs are analysed in [9], [69] with a distributed Kalman filter in the former and a Luenberger observer in the latter. Finally, [2] considers a descriptor linear time-invariant system whose outputs can be compromised by false data injection attacks. The authors combine a Luenberger observer and an H_∞ filter to detect the attack and be resilient to its effect.

It is worth mentioning the work [25], which studies a different situation in which the attacks directly affect the estimator dynamics:

$$\dot{\hat{x}}_i(t) = Ax_i(t) + L_i(y_i(t) - C_i\hat{x}_i(t)) + K_i \sum_j (\hat{x}_j(t) - \hat{x}_i(t)) + f_i(t), \tag{2.5}$$

with $f_i(t)$ the signal attack to be detected using, in this case, a distributed H_∞ filter.

Jamming attack: This sort of attack pursues to block the wireless transmission channels between sensors and remote estimators, incurring in a possible packet loss or a partial degradation of the information. Therefore, it is considered a situation in which the sensors are not physically located near the agent, unlike the previous cases.

To model jamming attacks, the authors in [34] use the following formulation:

$$\hat{y}_i(k) = y_i^{attk}(k) + y_i^{comp}(k) + D_i v_i(k), \quad \forall i, \tag{2.6}$$

where the corrupted measurement $\hat{y}_i(k)$ that the remote estimator receives consists of two terms plus a noise:

$$\begin{aligned} y_i^{attk}(k) &= \theta_i(k) y_i(k), \\ y_i^{comp}(k) &= (1-\theta_i(k))\hat{y}_i(k-1), \end{aligned} \tag{2.7}$$

and specifically:

- $y_i^{attk}(k)$ stands for the attacked and manipulated measurement term. Signal $y_i(k)$ is the actual output measured by the sensor.
- $y_i^{comp}(k)$ represents the compensated measurement term corresponding to the lossy measurement $y_i^{attk}(k)$ caused by the attacker.
- $v_i(k)$ denotes the measurement noise experienced through the wireless channel.

The stochastic variable $\theta_i(k)$ takes values of 1 and 0, with $\theta_i(k) = 0$ representing the case of a jamming attack.

With the assumption of $\theta_i(k)$ being a Bernoulli distributed white sequence, with known expected value $E\{\theta_i(k)\} = \beta_i$, a measurement compensation unit is proposed in [34] for this kind of attack. It is based on a buffer that stores past data that are used in case of attacks.

To tackle the random jamming attacks, a refined measurement output model based on compensated measurements has been proposed and resilient estimators have been constructed.

Fake communications: with this name we refer the situation in which the attacker is able to gain control of a communication link to substitute real packets or to inject extra packets when two agents or estimators interchange some sort of information. It is, therefore, an attack that takes place in the cyber layer. Secure estimators for this sort of attacks is presented in [2], [28], [69].

Denoting by $\mathcal{Z}_{i,j}(k)$ the information that agent i receives from agent j, fake communication are modeled in [28] as:

$$\mathcal{Z}_{i,j}(k) = \mathcal{Y}_{i,j}(k) \cup \mathcal{F}_{i,j}(k), \tag{2.8}$$

where

$$\mathcal{Y}_{i,j}(k) = \begin{cases} y_{i,j}(k) & \text{no attack} \\ 0 & \text{complete packet substitution} \\ \tilde{y}_{i,j}(k) & \text{packet modification} \end{cases},$$

and $\mathcal{F}_{i,j}(k)$ is the set of any fake packet originated by the attacker.

In particular, the paper [28] analyses a cluster-based network, wherein multiple cluster-heads receive data from remote sensors via non-secure links and exchange processed information neighbourwise via secure links.

Fake communications are also considered in [2], in which the authors introduce a specific cyber-attack on the communication links between monitoring centres, in addition to false data injection sensor attacks. The novel Kullback-Liebler divergence based detector is used in [69] to capture the fake communications.

Fake agent: this is the case where either the attacker has gained control of an agent or the agent itself is the attacker. In both cases, the information that this agent sends to the rest of estimators can be compromised.

A trust-based mechanism is proposed in [45], [60] to cooperatively detect the fake agent and reduce the impact of the information received from it, in the first case through a Kalman filter, while in the second with a Luenberger observer. A similar version of the fake agent can be found in [65] under the name of Byzantine adversaries. In this case, the problem is analysed using a distributed Luenberger observer based on subspace decomposition. This kind of Byzantine agent is given complete knowledge of the network and system dynamics and is allowed to deviate from the rules of any prescribed algorithm. Sufficient conditions for state estimation are provided in [65], relying on the construction of a directed acyclic graph. In this paper, the authors allow for the possibility that certain nodes in the network are compromised by an adversary and do not follow their prescribed state estimate update rule.

Two subsets of V (set of nodes) are created: R comprising of regular nodes and $A = V \setminus R$ comprising of adversarial nodes. They consider the Byzantine fault model where an adversarial node can arbitrarily deviate from the rules of any prescribed algorithm and can transmit different state estimates to different neighbours at the same time step. In addition, the adversarial nodes possess complete knowledge about the graph topology and the plant dynamics, i.e., an adversarial node knows the measurements of the normal nodes at every time step. They endow such privileges to the adversaries with the aim of providing resilience to worst-case behavior. This is known in the literature, as the f-total adversarial model.

Definition 2.4.1. *(Omniscience) [41] A distributed observer achieves omniscience if* $\lim_{k\to\infty} \|\hat{x}_i(k) - x(k)\| = 0, \quad \forall i \in \{1, \dots, N\}$*, i.e., the state estimate maintained by each node asymptotically converges to the true state of the plant.*

Definition 2.4.2. *(f-local set) [41] A set* $C \subset V$ *is f-local if it contains at most f nodes in the neighbourhood of the other nodes, i.e.,* $|N \cap C| \leq f, \forall i \in V \setminus C$*.*

Definition 2.4.3. *(f-local adversarial model) [41] A set A of adversarial nodes is f-locally bounded if A is an f-local set.*

Considering the following system:

$$\begin{aligned} x(k+1) &= Ax(k), \\ y_i(k) &= C_i x(k), \end{aligned} \tag{2.9}$$

the problem in [65], is to formulate a state estimation scheme so that

$$\lim_{k \to \infty} \|\hat{x}_i(k) - x(k)\| = 0 \quad \forall i \tag{2.10}$$

regardless of the actions of any f-locally bounded set of Byzantine adversaries.

- Fault detection and isolation (FDI), are found in [83], [90]. In [90] a new algorithm is proposed for distributed fault detection and isolation, applicable to systems of systems based on Kalman filter. The mathematical formulation for a fault detection and isolation system with q faults presented in [90] is:

  $$\begin{aligned} \dot{x}(t) &= Ax(t) + \Gamma w(t) + \sum_{k=1}^{q} \bar{F}_k \bar{\mu}_k(t), \\ y(t) &= Cx(t) + v(t), \end{aligned} \tag{2.11}$$

  where x, y, w, v are the state, output, input and measurement noise vectors, respectively, of the system.

The authors assume that there is one target fault to be detected by every agent $i \in 1, \ldots, q$, denoted $\mu_1(t) = \bar{\mu}_i(t)$; the rest of the faults represent the nuisance fault μ_2, i.e., $\sum_{k=1}^{q} \bar{F}_k \bar{\mu}_k(t) = F_1\mu_1(t) + F_2\mu_2(t)$.

The main contribution of [83] is the design and analysis of a fault diagnosis methodology, with emphasis on the distributed isolation of multiple sensor faults that may affect the physical part of multiple interconnected cyber-physical systems, which may exchange sensor information related to the physical interconnections. This methodology builds upon a distributed Luenberger observer.

- Other applications: in this group, three particular studies not related to the previous groups were included. In [82], the authors propose a new approach for 3D upper body pose estimation, using a combination of an annealing particle filter and belief propagation inference. The work [21] is concerned with the distributed estimation problem, adopting a Kalman-like filter, for industrial automation over relay assisted wireless sensor networks. Finally, in [7] a biological system is considered. In this work, the authors present a framework for the use of a wireless sensor network as an estimator of the biofilm evolution in a reverse osmosis membrane so that effective solutions can be applied before the irreversible phase is attained.

TABLE 2.11: Features table. Fields of application of the surveyed studies

Application	Studies
Heterogeneous multi-agent system	[13], [26], [59], [67], [96]
Fault detection and isolation	[83], [90]
Attack detection	[2], [8], [9], [25], [28], [34], [69]
Secure estimation	[8], [9], [28], [34], [45], [60], [65]
Others	[82] 3D Upper body pose estimation [21] Monitoring industrial CPSs [7] Biological system

RQ.3.1: In applications that include humans, animals or biological systems, which estimator obtains better results?

While the review has been targeted at this kind of application, not many items have been found that include humans, animals or biological systems. Consequently, it is not possible to make real comparisons or to extract the best conclusions. For instance, no paper was found that includes animals in the application.

We must firstly mention [7], which uses a distributed Kalman filter for a biological system. In particular, the authors present a deployment of a wireless sensor network to estimate the biofilm evolution in a reverse osmosis membrane. They obtain nice results in simulation. However, in order to extract valuable conclusions, experimental validation is required.

Another paper that satisfies this requirement is [13]. It presents a coordinated network of humans and robots for state estimation using a Bayesian filter. Peer-to-peer collaboration between human–computer augmented nodes and autonomous mobile sensor platforms happens by sharing information via wireless communication network. The proposed method is tested with experiments, which shows that improved results are obtained due to the human–robot collaboration.

2.4.2 Strengths and Weaknesses

This study presents several weaknesses, some that are typically common to all SRs and others that appear due to the inexistence of this kind of review applied to our field:

- With the aforementioned criteria, five digital databases have been chosen to include as many relevant papers as possible. However, all published papers on the topic cannot be analysed, limiting the review conducted.
- Another possible weakness might be the inclusion and exclusion criteria adopted for selecting papers. For example, this work focused on papers published in English, but there might be relevant studies written in other languages.

- Many databases are not prepared for such an accurate research as the one described in Subsection 2.3.3.1.
- There exists no normalisation for the contents of abstract and title in control and automation journals and conferences, a problem shared with other fields, such as computer science. Moreover, although the keywords are sometimes normalised, they are not usually peer-reviewed. This makes it difficult to make a correct screened reading just title and abstract. Then, full text must be reviewed, so the time devoted in the very first phases of the review is really large. In contrast, the abstract of many social science papers must include, for instance, explicit reference to objectives, methods, results and conclusions; this eases the screening process.
- When extracting the data, it is often harder to compare two techniques or two aspects treated differently to in other sectors, such as medicine or psychology, where mainly studies and/or clinical data are compared. Thus, a qualitative rather than a quantitative (for instance, a meta-analysis) comparison was made. A possible solution to this weakness would be the formulation of benchmark problems, in which the same problem would be faced with different approaches, so as to be able to extract adequate quantitative conclusions.

On the other hand, this SR presents some strengths that must be pointed out:

- From the author's knowledge, this is the first SR in automation and control, inheriting the good practices in areas in which these reviews are a common practice.
- The study follows the PRISMA guidelines for reporting SRs to meet the highest quality. As a consequence, the SR identifies all the relevant works produced on the topic following an explicit and reproducible research methodology.
- Some recommendations for the control community have been proposed: normalisation in the information included in the title, abstract and keywords; definition of benchmarks problems to make qualitative comparisons of different estimation techniques; or development of better search engines in the databases, just to mention some of them.

2.4.3 Detected Gaps and Future Research

The SR has discovered important gaps that should be filled in the following years and which inspired the following chapters of this thesis:

- Pure distributed H_∞-based attack detection mechanism: both papers that incorporate an H_∞-filter for attack detection require a centralized design based on LMIs [25], [34]. Providing a decentralized mechanism for the observer synthesis seems to be compulsory, specially in these frameworks in which a cyber-attack is able to disable an agent or its communications.

- Inclusion of matrix gains for consensus-based estimators: scalar gains [26], [28], [45], [65], [67], [96] and diagonal matrices [90] have been proposed in the literature to weight the consensus agreement. Using a complete matrix would be useful to differentiate the weights of the different components in the consensus. Decentralized design of these matrices must also be pursued. In fact, in [25] the authors propose the use of a consensus matrix, but it is common for all the agents and must be found by solving a centralized LMI.

- Modifications of the distributed Kalman filter with reduced communication effort: either because of the consensus iterations or the need of additional matrices (covariance or information matrices), the proposed DKF are the ones that rely on heavier communication effort to fulfill their objectives. Moving to DKF formulations in which just a subset of the complete state vector is sent should be an interesting goal for the next years.

- Privacy and security in CPS: some of the primary studies deal with the problem of secure estimation in the presence of attacks (see Table 2.11). However, nothing has been said about the privacy of the information exchanged between agents. Coping with these issues in an open environment, in which the wireless communications can suffer from any malicious action, must also be analysed in depth in the future.

- Lack of sliding mode observers and guaranteed estimators for CPS: none of the studies have used this kind of observer structure for the estimation of CPS. While they are very common in the literature, the SR concludes that more effort is necessary in the adaptation of those methodologies that have shown great success in the estimation of nonlinear models.

- Practical absence of estimators for biological, human and animal environments: as examined through the research question *RQ.3.1* only two studies have been found with this kind of application. This reveals, in the author's opinion, that the background of the researchers in estimation of CPS is greater in the cybernetic layer than in the physical one. Increased multi-disciplinary research must be done to fill this gap.

- Almost inexistence of complex models, such as hybrid systems, to describe the physical part of the CPS: while the modelling of complex systems has been the subject of intense research, this SR discloses that those formulations have not been used when the problem of distributed estimation of CPS is to be solved. In fact, most of the studies use linear models [2], [21], [25], [26], [45], [65], [67], [90]. Unfortunately, the inclusion of external human commands or the occurrence of a discrete event, are better captured with other structures.

In addition, the SR has presented some recommendations to the community, including editors or databases, that were mentioned before.

Once the main gaps and possible future research have been detected, precisely about these gaps, the following chapters have been chosen and developed. In fact, one of the objectives of this thesis is exactly to design a guaranteed observer, a distributed set-membership estimator for linear systems.

Chapter 3

Preliminaries of distributed set-membership estimation

The objective of the present Chapter is to introduce some concepts fundamental to the development of the thesis. Indeed, the main types of sets used in the set-membership estimators are herein described, highlighting those that will be used in the next chapter: zonotopes and constrained zonotopes. Furthermore, the main properties of these sets will be presented. Finally, the multi-hop decomposition of the state-space, indispensable for a clear understanding of Chapter 4, will be presented in Section 3.2.2.

3.1 Set-membership estimation

The set-membership approach is of great importance for applications of the control theory, and in automation in general: fault detection and isolation or fault diagnosis, just to cite some of them. A number of interesting papers was presented in the literature, such as [31], [97] to cite the most recent ones. In [97] a fault tolerant control with an online control allocation scheme is designed. In [31], the authors present a distributed set-membership estimation and formation control algorithm for a fleet of vehicles, where the agent's objective is to compute an estimation set for the state of all the fleet of vehicles and generate control actions to keep its local vehicle in formation. In this chapter we will concentrate only on its application in distributed estimation techniques.

3.1.1 Introduction of set-membership estimation

This work develops some estimation algorithms based on guaranteed techniques. This approach, also known as set-membership [63], is based on the construction of a compact set that includes with guarantee, the states of the systems that are consistent with the measured output and the bounded noise [4].

Instead of using assumptions about the statistical properties of the uncertainties like probabilistic approaches, often difficult to validate, a norm-bounded uncertainty is considered in set-membership estimation.

Filtering algorithms, like Kalman filter and its variants, or H_∞ filter and so on, do not guarantee that states are contained in a certain region because they do not provide hard bounds. Nevertheless, many practical applications, such as system guidance and navigation, target tracking and attack, require a confidence level of 100% in the estimation of the variables [53]. This leads to state estimation, using guaranteed set-membership techniques through different types of sets.

Compared to other filtering methods, as already mentioned, the set-membership filtering approach has two significant differences [53]:

- it requires a hard bound constraint rather than the statistical description on the system noise, and
- it is capable of providing a set that contains all possible actual states with 100% confidence.

From a technical point of view, such a set can be a convex polyhedron, which is usually described as a variety of simple shapes, such as ellipsoids, parallelotopes (intervals), polytopes (regular and irregular) and zonotopes among others.

3.1.2 Literature related to set-membership

The origin of set-membership filtering can be traced back to the 1960s [85], [94] and the corresponding problems have attracted the growing interest of many researchers.

Distributed set-membership observers aim to bound the variables to estimate under certain geometrical sets like intervals [20], [27], [61], ellipsoids [62], [99], and zonotopes [5], [19], [23], [51], [92]. The state of the art in distributed set-membership estimation is rather scarce.

In the pioneering work about set-membership estimation [85], an ellipsoidal bounding of the state of the dynamic system was proposed. Ellipsoids are widely used due to the simplicity of their formulation and resulting estimation stability properties [4]. Some more recent works with distributed estimators with ellipsoidal descriptions, can be found in [54], [57], [95] with different objectives. The authors in [54] use the Round-Robin communication protocol and the multi-rate strategy to regulate the different sampling rates in the estimation performance. An event-based communication mechanism over sensor networks is presented in [57]. Finally, the work [95] proposes a distributed set-membership estimation algorithm in which the ellipsoids locally computed by all the agents are merged in a global central unit. Secondly, interval observers have found application in the estimation of distributed power systems [98], and for spatially distributed systems described by partial differential equations [46].

In reference to distributed zonotopic estimation several works can be found, including [6], [24], [31], [75], [76], [92], [93]. Compared to interval descriptions or ellipsoids, zonotopes have the advantage of allowing for a trade-off between mathematical complexity and precision, through the number of generators used. Most of the works mentioned above, deal with the estimation of a system described by a set of interconnected subsystems, and the estimation goal of each agent is to construct sets containing the states of the local subsystem. This is the case of [24], [75], [76], [92], [93].
On the contrary, the papers [6], [31] present estimators able to reconstruct and wrap the whole state vector. The former proposes the use of diffusion techniques, that have been successfully applied in distributed Kalman filtering. The latter is based on the intersection of zonotopes. Remarkably, in [31] they tackle the joint problem of distributed estimation and control.

These two last papers [6], [31], together with [95], constitute the unique references, from the best of our knowledge that cope with the same problem as studied here, this is, to present a guaranteed distributed estimation method for full-coupled linear perturbed systems to be implemented in a set of distributed agents that need to communicate and collaborate to achieve their goal.

Remaining on the zonotopic formulations of the problem, there are several contributions for the case when the communications between agents are affected by delays [30], multi-rate communications [76], and bandwidth limited networks for which negotiation schemes between the agents become necessary [75]. In addition, [24], [93] proposed distributed zonotopic estimators for large scale-systems. Interestingly, the observer in [24] merges set-membership with Gaussian estimation. Perhaps the most interesting feature of the zonotopic observers is that the observers can be designed in a decentralized way, in contrast to the aforementioned ellipsoidal ones, in which centralized optimization problems need to be solved.

It should be mentioned that most of these results [24], [75], [76], [93], [95] have been developed for a description of the system that consists of a set of interconnected subsystems and, then, the estimation goals are simplified to the estimation of the local subsystem's state.

Constrained zonotopes were recently presented in [86]. Although it is a new class of sets, it has already been used extensively for different types of estimation [12], [79]. In [12], the authors propose a data-driven set estimator that consists of an offline learning phase to determine a state-propagation function $f(\cdot)$ directly from data, and an online estimation phase to perform a time update using $f(\cdot)$ and measurements iteratively to track the system state. A set-valued state estimation of nonlinear discrete-time systems with unknown-but-bounded process and measurement uncertainties is presented in [79]. However, there are no works that cope with the same problem as the one studied here, as far as we are concerned, that is, a distributed set-membership estimator for linear full-coupled systems affected by bounded disturbances.

3.1.3 Mathematical description of sets

The guaranteed estimation methodology can greatly improve the stability, robustness and reliability of the system, which makes the set-membership filter widely used in many fields such as robot localization and mapping neural networks training, fault diagnosis and so on [99]. A key problem in set membership methodology is how to describe the complicated shape of the true feasible set. Commonly, some canonical geometric sets, such as ellipsoid, interval, paralletope and zonotope, can be used to approximate the feasible set to reduce the complexity of the algorithm [99]. The mathematical descriptions of each of these sets is detailed below.

Definition 3.1.1. *[99] An n-dimensional interval vector or axis-aligned box is defined as:*

$$[x_{min}, x_{max}] = \Big\{x \in \mathbb{R}^n : \quad x_{i,min} \leq x_i \leq x_{i,max}, \quad i = 1, \dots, n\Big\},$$

where $x_{min} = [x_{1,min}, x_{2,min}, \dots, x_{n,min}]^\top$ *and* $x_{max} = [x_{1,max}, x_{2,max}, \dots, x_{n,max}]^\top$ *are the lower and upper bounds of the box, respectively. We can also rewrite previous equation as:*

$$B(a, r) = \Big\{x \in \mathbb{R}^n : \quad x = a + diag(r)\xi, \|\xi\|_\infty \leq 1\Big\},$$

where $a = (x_{min} + x_{max})/2$*, is the centre of the interval vector (or box);* $r = (x_{min} - x_{max})/2$ *is the width of interval vector which denotes the size of the edges of the box.*

Definition 3.1.2. *[99] An n-dimensional parallelotope can be defined as:*

$$P(a, T) = \Big\{x \in \mathbb{R}^n : \quad x = a + T\xi, \|\xi\|_\infty \leq 1\Big\},$$

where $a = (x_{min} + x_{max})/2$ *is the centre of the parallelotope;* $T \in \mathbb{R}^{n\times n}$ *is a nonsingular matrix with columns denoting the edges of the parallelotope.*

Definition 3.1.3. *[22] A polytope P is given by the intersection of m strips. This is written as:*

$$P = \cap_{i=1}^{m} F_i(c, d)$$

where

$$F_i(c, d) = \Big\{x \in \mathbb{R}^n : \quad |c^\top x - d| \leq 1\Big\},$$

with $c \in \mathbb{R}^{n\times m}$*,* $d \in \mathbb{R}^m$*.*

In the case $n = m$ the simplest bounded polytope is called a parallelotope.

Definition 3.1.4. *[99] An n-dimensional ellipsoid $E(a,P)$ is defined as:*

$$E(a,P) = \Big\{x \in \mathbb{R}^n : \quad (x-a)^\top P^{-1}(x-a) \leq 1\Big\},$$

where $a \in \mathbb{R}^n$ is the centre of the ellipsoid and the envelope matrix $P \in \mathbb{R}^{n\times n}$ is a positive definite symmetric matrix which determines the shape of the ellipsoid.

Remark 3.1.1. The size of an ellipsoid $E(a,P)$ is often measured by means of volume, which is proportional to $det(P)$, or sum of squared semi-axes lengths, which is given by the trace of the envelope matrix $tr(P)$.

Definition 3.1.5. *[4] A zonotope $\mathcal{X}$, is a centrally symmetric convex set determined by its centre $c \in \mathbb{R}^n$, and by a matrix $H \in \mathbb{R}^{n\times p}$:*

$$\mathcal{X} = \langle c, H\rangle = \{c + H\xi : ||\xi||_\infty \leq 1\},$$

where $h_i \in \mathbb{R}^n$ (columns of H) are called generator vectors.

Definition 3.1.6. *[86] A set $\mathcal{Z} \subset \mathbb{R}^n$ is a constrained zonotope if there exists $\langle c, H, G, b\rangle \in \mathbb{R}^n \times \mathbb{R}^{n\times n_g} \times \mathbb{R}^{n_c\times n_g} \times \mathbb{R}^{n_c}$ such that:*

$$\mathcal{Z} = \{c + H\xi : ||\xi||_\infty \leq 1, G\xi = b\}.$$

This equation represents the constrained generator representation, in which each column of H is a generator, c is the centre, and $G\xi = b$ are constraints.

As it can be seen from the previous equations, every zonotope is a constrained zonotope, with the parameter $G = 0$ and $b = 0$.

3.1.4 Basic set operations with zonotopes

Taking up the mathematical formulation of a zonotope in the Definition 3.1.5 [4]: a zonotope $\mathcal{X}$, denoted with calligraphic capital letters, is a centrally symmetric, convex set determined by its centre $c \in \mathbb{R}^n$, and by a matrix $H \in \mathbb{R}^{n\times b}$, (see Figure 3.1):

$$\mathcal{X} = \langle c, H\rangle = \{c + H\xi : ||\xi||_\infty \leq 1\} \tag{3.1}$$

where $h_i \in \mathbb{R}^n$ (columns of H) are called *generator vectors*.

Figure 3.1 is the representation of a zonotope with $c = 0$ and $H = [h_1, h_2, h_3]$, where $h_1 = [2,0,0]^\top$, $h_2 = [0,2,0]^\top$ and $h_3 = [0,0,1]^\top$.

The *order* of a zonotope is given by the number of generator vectors.

The *F-radius* of a zonotope is the Frobenius norm of its generator matrix H, this is, $||H||_F = \sqrt{tr(H^T H)}$. Operator $tr()$ is the trace of a matrix and the *covariation* of a zonotope is defined as $P_\mathcal{X} = HH^T$ (see [23]).

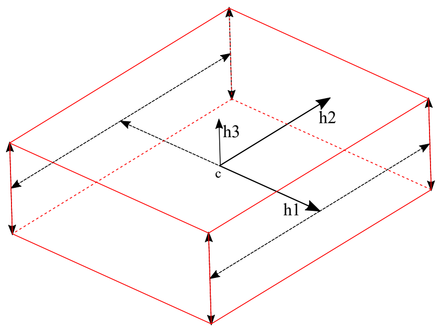


FIGURE 3.1: Representation of a zonotope

Let $\mathcal{X} = \langle c, H \rangle$ and $\mathcal{Y}_i = \langle c_i, H_i \rangle$, $i = 1, \dots, n$ be respectively a zonotope and a set of zonotopes, and let R be a matrix of appropriate dimensions. A linear transformation of a zonotope is given by:

$$R\mathcal{X} = \langle Rc, RH \rangle, \tag{3.2}$$

and the Minkowski sum of several zonotopes is obtained as:

$$\bigoplus_{i=1}^{n} \mathcal{Y}_i = \bigoplus_{i=1}^{n} \langle c_i, H_i \rangle = \langle c_y, H_y \rangle, \tag{3.3}$$

with $c_y = \sum_{i=1}^{n} c_i$ and $H_y = \text{cat}_{i=1}^{n}\{H_i\}$.

Given a matrix A and any vectors such that $x \in \mathcal{X}$ and $w \in \mathcal{W}$, it holds that

$$y := Ax + w \in A\mathcal{X} \oplus \mathcal{W}. \tag{3.4}$$

3.1.4.1 Order reduction of zonotope

The operator $red_q(\mathcal{X})$, is an order reduction of the zonotope $\mathcal{X}$ in such a way that $\mathcal{X} \subseteq red_q(\mathcal{X})$, and the order of $red_q(\mathcal{X})$ is q. Several methods have been proposed to carry out the reduction of order of the zonotope, such as [23] and [49]. In this work we will use [23] for its simplicity, provided that this is not the purpose of this thesis.

The reduction operator defined in [23] first consists in sorting the column of $H \in \mathbb{R}^{n \times b}$ on decreasing weighted vector norm:

$$H = [h_1, \dots, h_j, \dots, h_b], \qquad ||h_j||^2 \geq ||h_{j+1}||^2,$$

and enclosing the set $\langle H_< \rangle$ generated by $b - q + n$ smaller columns into a box:

$$red_q\langle c, H \rangle = \begin{cases} \langle c, H \rangle & \text{if} \quad b \leq q \\ \langle c, [H_> \quad box(H_<)] \rangle & \text{if} \quad b > q \end{cases}$$

where $H_> = [h_1, \ldots, h_{q-n}]$, $H_< = [h_{q-n+1}, \ldots, h_b]$ and $box(H) \in \mathbb{R}^{n\times n}$ is computed as

$$box(H) = \begin{bmatrix} \sum_{j=1}^{b} |h_{1j}| & \ldots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \ldots & \sum_{j=1}^{b} |h_{bj}| \end{bmatrix}$$

Theorem 3.1.1. *[23] Let $H \in \mathbb{R}^{n\times b}$ be the generator matrix of a zonotope $\mathcal{X}$. Let $\mathcal{W} \in \mathbb{R}^{n\times n}$ be a positive definite matrix with all its eigenvalues $\in [\underline{\lambda}, \bar{\lambda}] \subset \mathbb{R}$. Let $n \le q < b$ and $red_q(\mathcal{X}) = \langle c, [H_> \quad box(H_<)] \rangle$ be the order reduction of $\mathcal{X}$ with at most q generators. Then, it holds:*

$$||red_q(\mathcal{X})||^2_{F,W} - ||\mathcal{X}||^2_{F,W} \le \frac{\mu}{b} ||\mathcal{X}||^2_{F,W},$$

where $\mu = (\frac{\bar{\lambda}}{\underline{\lambda}}(b-q+n) - 1)(b-q+n)$.

The proof of this theorem can be found in [23].

3.1.5 Basic set operations with constrained zonotopes

Taking up the mathematical formulation of a constrained zonotope in Definition 3.1.6, as defined in [86], a set $\mathcal{Z} \subset \mathbb{R}^n$ is a constrained zonotope if there exists $\langle c, H, G, b \rangle \in \mathbb{R}^n \times \mathbb{R}^{n\times n_g} \times \mathbb{R}^{n_c \times n_g} \times \mathbb{R}^{n_c}$ such that

$$\mathcal{Z} = \{c + H\xi : ||\xi||_\infty \le 1, G\xi = b\}. \tag{3.5}$$

In Figure 3.2 a constrained zonotope is represented by the yellow plane. It has been obtained by applying the restriction $G = [1, -1, 0]$ and $b = 0$ to zonotope of Figure 3.1.

Definition 3.1.6 permits linear equality constraints on ξ. Equation (3.5) represents the constrained generator representation, in which each column of H is a generator, c is the centre, and $G\xi = b$ are constraints.

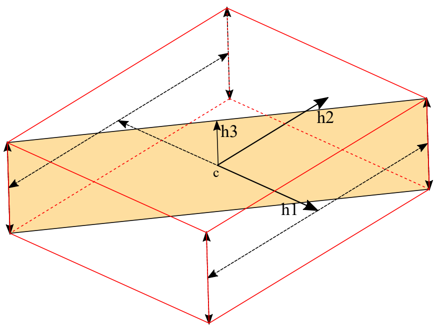


FIGURE 3.2: Representation of a constrained zonotope

Let $\mathcal{Z} = \langle c_z, H_z, G_z, b_z \rangle \subset \mathbb{R}^n$ and $\mathcal{W} = \langle c_w, H_w, G_w, b_w \rangle \subset \mathbb{R}^n$. Let $y = Cz + v \in \mathbb{R}^m$ be a measured output sequence, where $C \in \mathbb{R}^{m\times n}$, and $v \in \langle 0, R_i \rangle$. Let $\mathcal{Y}$ be the range of states consistent with y and $R \in \mathbb{R}^{k \times n}$. Then, these four identities hold, as demonstrated in [86]:

$$R\mathcal{Z} = \langle Rc_z, RH_z, G_z, b_z \rangle, \tag{3.6}$$

$$\mathcal{Z} \oplus \mathcal{W} = \left\langle c_z + c_w, [H_z \quad H_w], \begin{bmatrix} G_z & 0 \\ 0 & G_w \end{bmatrix}, \begin{bmatrix} b_z \\ b_w \end{bmatrix} \right\rangle, \tag{3.7}$$

$$\mathcal{Z} \cap \mathcal{W} = \left\langle c_z, [H_z \quad 0], \begin{bmatrix} G_z & 0 \\ 0 & G_w \\ H_z & -H_w \end{bmatrix}, \begin{bmatrix} b_z \\ b_w \\ c_w - c_z \end{bmatrix} \right\rangle. \tag{3.8}$$

$$\mathcal{Z} \cap \mathcal{Y} = \left\langle c_z, [H_z \quad 0], \begin{bmatrix} G_z & 0 \\ CH_z & -v \end{bmatrix}, \begin{bmatrix} b_z \\ y - Cc_z \end{bmatrix} \right\rangle. \tag{3.9}$$

3.1.5.1 Order reduction of constrained zonotope

The operator $red_{q,qr}(\mathcal{Z})$, is an order reduction of constrained zonotope $\mathcal{Z}$. Given a constrained zonotope $\mathcal{Z}$ and target orders q (desired order) and q_r (number of restrictions desired), reduction is performed by three steps [86] (for a complete description, the reader is referred to that paper) :

1. rescaling: the conservatism of constraint reduction can be significantly reduced by first transferring some information from the constraint data (G, b) to the generator data (c, H). To do this, the constraints are first used to tighten the bounds $||\xi||_\infty \leq 1$;

2. constraint reduction: constraints are eliminated until the number of restrictions is not smaller or equal that q_r. The proposed method for this step eliminates one generator for each eliminated constraint;

3. generator reduction: the number of generator vector is reduced to q desired.

The final result is a reduced constrained zonotope $\tilde{\mathcal{Z}} = red_{q,qr}(\mathcal{Z})$, satisfying $\mathcal{Z} \subset \tilde{\mathcal{Z}}$.

3.1.6 Main observations

Linear transformation (3.2, 3.6) and Minkowski sum (3.3, 3.7) are both closed operation using zonotopes or constrained zonotopes. However, intersection of constrained zonotopes (3.8) is a closed operation (as demonstrated in [86]), that is, it returns a constrained zonotope, while the intersection of zonotopes is not, although it is possible to find a zonotope enclosing this intersection (as detailed in [4], for instance). This is the main advantage of constrained zonotopes with respect to simple zonotopes.

The order reduction of zonotopes is an operation that depends only on the number of generator vectors and can be more or less complex depending on the chosen algorithm. On the other hand, order reduction for constrained zonotopes depends on two parameters, i.e. the number of generator vectors and the number of constraints. Consequently, the order reduction for constrained zonotopes is computationally more complex compared to simple zonotopes. Indeed to apply the algorithm in Section 3.1.5.1, step 3. shall be repeated as many times as the number of constraints.

3.2 Linear transformation for observability

A system in space-state form can be realized in several different ways and by means of coordinate transformations one can obtain the different realisations. Although the representation of the system is different in each case, a number of properties of the original system are invariant under such transformations [1].

The search for a transformation matrix T aims to consider a situation of changing from the existing state representation x to a new state representation $z = Tx$. This state transformation or "a change of variables" is used for several purposes: to simplify a calculation and/or to gain insight into a phenomenon.

Among the existing decompositions in the literature, there are the standard diagonalizability or also the Jordan normal form [36].

3.2.1 Introduction to observability

The solution presented in the following section relies on a subspace decomposition know as "Observability staircase form" [36], where each agent to identify its observable (x_o) and unobservable (x_{no}) subspace.

Consider a discrete-time LTI system:

$$x(k+1) = Ax(k) + Dw(k), \tag{3.10}$$

$$y(k) = Cx(k) + v(k), \tag{3.11}$$

where $x \in \mathbb{R}^n$ is the state vector, $y \in \mathbb{R}^m$ is the output locally measured by agent, $w \in \mathbb{R}^r$ represents disturbances or unmodeled dynamics, and $v \in \mathbb{R}^v$ is measurement noise and k the time step. Matrices A, D, C are constant matrices of appropriate dimensions.

We can define a transformation such that $z = T^{-1}x$, leading to

$$z(k+1) = \bar{A}z(k) + \bar{D}w(k), \tag{3.12}$$

$$y(k) = \bar{C}z(k) + v(k), \tag{3.13}$$

where $\bar{A} = T^{-1}AT$, $\bar{D} = T^{-1}D$, $\bar{C} = CT$.

The observability matrices $\mathcal{O}$ and $\bar{\mathcal{O}}$ of the systems (3.10)-(3.11) and (3.12)-(3.13), respectively, are related by

$$\bar{\mathcal{O}} = \begin{bmatrix} \bar{C} \\ \bar{C}\bar{A} \\ \vdots \\ \bar{C}\bar{A}^{n-1} \end{bmatrix} = \begin{bmatrix} C \\ CA \\ \vdots \\ CA^{n-1} \end{bmatrix} T = \mathcal{O}T. \tag{3.14}$$

Since the observability of a system is determined by the rank of its observability matrix, which does not change by multiplication by a nonsingular matrix, we obtain the following result.

Theorem 3.2.1. *[36] The pair (A, C) is observable if and only if the pair $(\bar{A}, \bar{C}) = (T^{-1}AT, CT)$ is observable.*

Theorem 3.2.2. *[36] For every LTI system* (3.10)-(3.11)*, there is a similarity transformation that takes the system to the form:*

$$\begin{bmatrix} A_o & 0 \\ A_{21} & A_{no} \end{bmatrix} = T^{-1}AT, \quad \begin{bmatrix} D_o & D_{no} \end{bmatrix} = T^{-1}D, \quad \begin{bmatrix} C_o & 0 \end{bmatrix} = CT, \tag{3.15}$$

for which

- *the unobservable subspace of the transformed system* (3.15) *is given by: $Im \begin{bmatrix} 0 \\ I_{\bar{n}\times\bar{n}} \end{bmatrix}$ where $\bar{n}$ denotes the dimension of the unobservable subspace of the original system, and*
- *the pair (A_o, C_o) is observable.*

By partitioning the state of the transformed system as:

$$z = T^{-1}x = \begin{bmatrix} x_o \\ x_{no} \end{bmatrix}, \qquad x_o \in \mathbb{R}^{n-\bar{n}}, x_{no} \in \mathbb{R}^{\bar{n}},$$

its state-space model can be written as follows:

$$\begin{bmatrix} x_o(k+1) \\ x_{no}(k+1) \end{bmatrix} = \begin{bmatrix} A_o & 0 \\ A_{21} & A_{no} \end{bmatrix} \begin{bmatrix} x_o(k) \\ x_{no}(k) \end{bmatrix} + \begin{bmatrix} D_o \\ D_{no} \end{bmatrix} w(k),$$

$$\begin{bmatrix} C_o & 0 \end{bmatrix} \begin{bmatrix} x_o(k) \\ x_{no}(k) \end{bmatrix} + v(k),$$

in which it highlights the fact that the x_{no} component of the state cannot be reconstructed from the output. Moreover, the observability of the pair (A_o, C_o)

means that the x_o component of the state can be uniquely reconstructed from the input and output [36].

The observability staircase form is valid only when an agent has a direct measurement $y(k)$. The multi-hop decomposition presented in the next section is a generalization to a distributed scheme, in fact it uses the output locally measured by different agent $y_i(k)$. Hence the need to introduce a new parameter, called *hop*, which is the distance (or steps) in the graph to arrive at the measurement taken by a random neighbour. If it is your direct neighbour, it has to take a single step to reach that agent, that is, $\rho = 1$.

3.2.2 Multi-hop decomposition

The multi-hop decomposition technique for state-estimation was recently introduced in [71]. Although some relevant details are described next, the reader is referred to that paper for a more complete description.

Consider a set of agents $\mathcal{V} = \{1, 2, \ldots, p\}$ connected according to a given bidirectional graph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$, with vertices $\mathcal{V} = \{1, 2, \ldots, p\}$ (agents) , and edges $\mathcal{E} \subseteq \mathcal{V} \times \mathcal{V}$ (communication links). The set of agents to which agent i is directly connected is named *the neighbourhood of* i, and is denoted by $\mathcal{N}_i := \{j : (i, j) \in \mathcal{E}\}$. Consider a discrete-time LTI (linear time invariant) system:

$$x(k+1) = Ax(k) + Dw(k), \tag{3.16}$$

$$y_i(k) = C_i x(k) + v_i(k), \tag{3.17}$$

where $x \in \mathbb{R}^n$ is the state vector, $y_i \in \mathbb{R}^{m_i}$ is the output locally measured by each agent, $w \in \mathbb{R}^r$ represents disturbances or unmodeled dynamics, and $v_i \in \mathbb{R}^v$ are measurement noises and k the time step. Matrices A, D, C_i are constant matrices of appropriate dimensions.

Given a set of matrices A_i, for $i = 1, \ldots, n$, of appropriate dimensions, operator $\operatorname*{cat}_{i=1}^{n}\{A_i\}$ implies the concatenation of the matrices, that is, $\operatorname*{cat}_{i=1}^{n}\{A_i\} = [A_1\ A_2\ \cdots\ A_n]$.

Definition 3.2.1. *The ρ-hop output matrix of agent i, $C_{i,\rho}$, is a matrix that stacks the $(\rho - 1)$-hop output matrix of agent i and the $(\rho - 1)$-hop output matrices of its neighbourhood, $\mathcal{N}_i$. That is:*

$$C_{i,\rho} := \begin{bmatrix} C_{i,\rho-1} \\ \text{cat}\{C_{j,\rho-1}^\top\}_{j \in \mathcal{N}_i}^\top \end{bmatrix}, \ \forall \rho \geq 1,$$

where $C_{i,0} := C_i$.

For any agent, there exists a coordinate transformation matrix $[\bar{V}_{i,\rho}\ V_{i,\rho}] \in \mathbb{R}^{n \times n}$ according to the pair $(C_{i,\rho}, A)$ such that the change of variable $z_{i,\rho} \triangleq [\bar{V}_{i,\rho}\ V_{i,\rho}]^\top x \in$

$\mathbb{R}^n$ transforms the original state-space representation into the observability staircase form.

Definition 3.2.2. *The ρ-hop unobservable subspace from agent i, denoted $\bar{\mathcal{O}}_{i,\rho}$, is composed of all system modes that cannot be observed from the output locally measured by agent i and those measured by all the agents belonging to the s-hop reachable set of i, $\forall s \in \{0,\dots,\rho\}$. Equivalently, the ρ-hop unobservable subspace from agent i is the unobservable subspace related to pair $(C_{i,\rho}, A)$ using the above coordinate transformation:*

$$\bar{\mathcal{O}}_{i,\rho} := Im(\bar{V}_{i,\rho}).$$

The orthogonal complement of $\bar{\mathcal{O}}_{i,\rho}$ is denoted ρ-hop observable subspace from agent i, $\mathcal{O}_{i,\rho} := Im(V_{i,\rho})$.

According to previous definitions, it is clear that:

$$\mathcal{O}_{i,\rho-1} \subseteq \mathcal{O}_{i,\rho}, \quad \forall i \in \mathcal{V}, \quad \rho \geq 0, \tag{3.18}$$

where we consider $\mathcal{O}_{i,-1} = \emptyset$. Then, the vectors of the "innovation" basis that generates $\mathcal{O}_{i,\rho} \cap (\mathcal{O}_{i,\rho-1})^{\perp}$ can be stacked into a matrix $W_{i,\rho}$ in such a way that:

$$Im(W_{i,\rho}) := \mathcal{O}_{i,\rho} \cap (\mathcal{O}_{i,\rho-1})^{\perp}, \quad \rho \geq 0, \tag{3.19}$$

Let us define $\ell_i \in \mathcal{Z}_{>0}$ as an arbitrary number of hops. From these definitions it is clear that for all $\rho \in \{0,\dots,\ell_i\}$ and all $i \in \mathcal{V}$, it holds that

$$Im(V_{i,\rho}) = Im\left(\begin{bmatrix} W_{i,\rho} & V_{i,\rho-1} \end{bmatrix}\right), \tag{3.20}$$

$$Im(\bar{V}_{i,\rho-1}) = Im\left(\begin{bmatrix} W_{i,\rho} & \bar{V}_{i,\rho} \end{bmatrix}\right), \tag{3.21}$$

with $\bar{V}_{i,-1} := I_n$.

It is worth pointing out that $Im(W_{i,\rho})$ corresponds to the innovation introduced by the ρ-hop reachable set of agent i, that is, the observable modes for agent i at hop ρ that are not observable at hop $\rho - 1$.

Property 3.2.1. *According to Lemma 3 in [71], it is satisfied $W_{j,\rho-1}^{\top} W_{i,r} = 0, \forall r > \rho$.*

Proposition 3.2.1. *For each agent i, the orthogonal similarity transformation given by*

$$T_i := \begin{bmatrix} \bar{V}_{i,\ell_i} & W_{i,\ell_i} & \cdots & W_{i,\rho+1} & W_{i,\rho} & \cdots & W_{i,0} \end{bmatrix}, \tag{3.22}$$

being ℓ_i the number of hops so that the pair (A, C_{i,ℓ_i}) is detectable, transforms the system matrix A into a block upper-triangular matrix in the form:

$$T_i^\top A T_i = \begin{bmatrix} \bar{V}_{i,\ell_i}^\top A \bar{V}_{i,\ell_i} & \bar{V}_{i,\ell_i}^\top A W_{i,\ell_i} & \cdots & \bar{V}_{i,\ell_i}^\top A W_{i,1} & \bar{V}_{i,\ell_i}^\top A W_{i,0} \\ 0 & W_{i,\ell_i}^\top A W_{i,\ell_i} & \cdots & W_{i,\ell_i}^\top A W_{i,1} & W_{i,\ell_i}^\top A W_{i,0} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & W_{i,1}^\top A W_{i,1} & W_{i,1}^\top A W_{i,0} \\ 0 & 0 & \cdots & 0 & W_{i,0}^\top A W_{i,0} \end{bmatrix}. \quad (3.23)$$

Algorithm 3.1 presents the initialization algorithm that must distributedly run so that each agent is able to get its own subspace decomposition. It represents an iterative process in which the agents compute and share matrices $W_{i,\rho}$ until hop $\rho = \ell_i$ is reached. Once this initialization phase is finished, each agent will have constructed all its innovation matrices $W_{i,\rho}, \forall \rho = 0, \ldots, \ell_i$, and will have received the innovation matrices $W_{j,\rho}, \forall \rho = 0, \ldots, \ell_j$ of its neighbours. For more details of the initialization algorithm, the reader is referred to Section 6 of [71].

Algorithm 3.1: Initialization algorithm

a) Construct $\mathcal{O}_{i,0}$ and compute $W_{i,0}$. Set $\rho = 0$
b) Perform the two steps:
  – Exchange $W_{i,\rho}$ with the neighbours.
  – Construct $\mathcal{O}_{i,\rho+1}$ and compute matrix $W_{i,\rho+1}$
c) Increment ρ and go to **b)** until hop $\rho = \ell_i$.
d) Exchange ℓ_i with the neighbourhood $\mathcal{N}_i$

Chapter 5

Conclusions

This final chapter summarises the main achievements of the work. Potential weaknesses and limitations as well as some possible future research lines are presented.

5.1 Main achievements

The most important results of this work are highlighted herein:

1. A protocol has been defined to carry out a systematic review in the field of systems and automatic engineering. Inspired by the available literature in SR on other disciplines, this thesis proposes the necessary modifications to adapt them to the considered field, in particular: description of the kind of search that can be done and the coverage of the available engineering databases, adaptation of the inclusion and exclusion criteria, explanation of booleans operators for the search and consequent definition of the boolean function, etc.

2. An updated systematic review of the distributed estimation techniques applied to cyber-physical systems, system of systems and heterogeneous systems that have been published in the period of time from the early 1990s to September 2019, is presented. The studies that have been included have been analysed to respond to the research questions posed, that is, what the techniques applied are, what their advantages and limitations are and in which field they have been applied. These results have been included in several tables to illustrate the findings. Moreover, the SR has detected existing gaps in the literature and the authors proposed some future research pathways to the community.

3. A distributed set-membership estimator for linear full-coupled systems affected by bounded disturbances is presented. The estimator uses a multi-hop staircase decomposition, capturing the locally unobservable subspaces in a cascaded fashion with the information incoming from other agents involved in the network. Each agent has to find different sets for each subspace, that are mathematically described by zonotopes. The observer gains that

minimise the size of those sets, i.e. the estimation uncertainty, can be designed in independent distributed steps by means of a simple algebraic equation. An important benefit of the proposed structure is the reduction of the computational requirements with respect to existing solutions.

4. A distributed set-membership estimation strategy is introduced. Like the algorithm presented above, the estimator uses a multi-hop decomposition, decoupling the influence of the non-observable modes to the observable ones. Thus, each agent has to find two different sets, for the locally and non-locally observable sub-spaces, that are mathematically described by constrained zonotopes. The proposed estimation algorithm can be applied directly to periodic, multi-rate, event-based or fully asynchronous communication schemes.

5.2 Weaknesses and limitations

The main strengths and potential weaknesses of systematic review were listed and discussed in Section 2.4.2. Some of them are common to all SRs while others are due to the inexistence of this kind of review applied to automatic and systems engineering.

Regarding the estimators, the main drawback is derived from the multi-hop decomposition used by both Algorithms 4.1 and 4.3 which allows the observer to reconstruct the whole state by using the minimal source of information coming from selected neighbours agents. This aspect is positive when dealing with networks highly disturbed by cyber-attacks or also when the communication rate is low and minimisation of information exchange is crucial. On the other hand, it can also be a limitation when considering the case in which a distributed algorithm is used to estimate the state of a perturbed system. Indeed, it must be taken into account that the measurement done by each agents can be strongly influenced by noise and that the agents interconnected network may be not limited. This means that there are no limitations in terms of volume of information and transmission speed. In this conditions, being selective with the information that each agent uses to reconstruct the state is not advantageous, as using a data-fusion algorithm which considers also redundant measurement, would result in a better estimation of the system's state. Obviously it comes at the cost of an increased computational load.

Another important limitation is due to the fact that the presented estimators are valid only for LTI systems. In the case of being the system non-linear or time-variant, then multi-hop decomposition would not be straightforward. At this point there are two options:

- Non-Linear systems: a non-linear observability analysis should be carried out;
- Time-Variant systems: a switched-system formulation could be used.

5.3 Further work

The main gaps that have been identified with the systematic review are exposed in Section 2.4.3. Hopefully, they will be filled during the next years.

Concerning distributed set-membership filtering, some further progress of the work are envisioned:

- Analysing the robustness of the estimators against delays and data dropouts as can be commonly found in real systems. This could be particularly helpful in making the developed algorithms more resilient when used in conjunction with low-quality or limited bandwidth networks.
- Designing and performing analysis of a distributed observer that takes into account redundant information to improve state estimation, above all when dealing with networks with no limitation in bandwidth and computational power.
- Developing new techniques to cope with situations where agents may receive unreliable data from their neighbours due to the fact that some agents may become faulty.
- Extending formulation of both Algorithms 4.1 and 4.3 to non-linear systems, in order to greatly extend their applicability to a wider set of estimation problems.

Appendix A

Distributed Estimation Techniques for Cyber-Physical Systems: A Systematic Review

sensors

MDPI

Review

Distributed Estimation Techniques for Cyber-Physical Systems: A Systematic Review

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Abstract: This paper undertakes a systematic review (SR) on distributed estimation techniques applied to cyber-physical systems (CPS). Even though SRs are not the common way to survey a theme in the control community, they provide a rigorous, robust and objective formula that should not be always ignored. The presented SR incorporates and adapts the guidelines recommended in other fields (mainly biosciences and computer sciences) to the field of automation and control and presents a brief description of the different phases that constitute an SR. As a result, this review compares the different techniques found in the literature in terms of: The proposed estimator (Kalman filter, Luenberger observer, Bayesian filter, etc.), the particular application within CPS, the design of the estimators (decentralized vs centralized), the amount of data required for implementation or the inclusion of experiments/simulations in the studies. Particular attention is paid to those papers that present some results in applications that include humans, animals or biological systems.

Keywords: cyber-physical systems; distributed estimation; systematic review

1. Introduction

The need to undertake a thorough and complete review on a given topic arises to reinforce the basic knowledge and, above all, the evolution and improvements that have taken place over the years. The large amount of information available makes it surprisingly difficult to review a precise research topic in an appropriate manner. Some of the common issues are related to the subjectivity of the reviewer, the lack of normalisation between the authors or the way in which the databases are searched. Hence, a systematic review (SR) or sometimes called systematic literature review, arises as a possible solution, since it has been applied with great success in other fields.

An SR is a form of secondary study, whereas individual studies, which contribute to the systematic review itself, are termed primary studies [1]. An SR focuses on one or more specific research question on the topic to be treated, using only primary studies related to the subject. The thematic areas that already use this kind of review range from medicine to economics, from psychology to software engineering. However, in our area of interest, automation and control, traditional survey papers are dominant. These narrative reviews are usually performed by researchers with extensive experience and knowledge in the field, providing their global or general view of the topic, see for instance [2–4]. While the latter is characterised by exploiting the experts' knowledge and their broad point of view, the former is distinguished by its objectivity and rigorousness.

In this paper, we inherit and adjust the good practices described in the bio-science [5,6] and computer science [1,7,8] literature to the particular features of our field. In addition, we adapt the PRISMA method (preferred reporting items for systematic reviews and meta-analyses) [9], to establish fundamental procedures to draw up the SR. This constitutes the first goal of the paper.

As the second and main objective, this paper aims to apply this methodology in order to review the distributed estimation techniques that have been applied to cyber-physical systems (CPS). Cyber-physical systems are complex systems composed of entities of different natures that interact with a given physical medium [10]. They can simultaneously have communication, computation and control capabilities and they can involve humans, animals and biological process [3]. Distributed estimation techniques aim to know the inner state of a system by using the information provided by the measurements locally collected from the plant and that information interchanged with the rest of agents [11].

To be more precise, we are interested in those heterogeneous systems that incorporate a physical part and a cybernetic layer. We are focused on the estimation of dynamical systems, so those papers that propose static estimators, such as those referred to in [12], are not included in the review. Another key feature of this SR is the fact that the distributed estimators must exchange some sort of information with other agents, in such a way that pure decentralised schemes (without communication) or sensor fusion techniques (all the information is gathered at a single node) are excluded. These constitute, mainly, the inclusion criteria for the studies appearing in the review.

After screening more than 2800 possible papers, only 20 primary studies satisfy the aforementioned criteria. We have carefully revised those papers and have collected the following data: The sort of estimator used (Kalman filter, Luenberger observer, Bayesian filter, etc.), the design of the estimators (if decentralised or centralised), the amount of data that must be exchanged between agents, the communication protocol (all-to-all, scheduled, just with neighbors, etc.), the particular application, the inclusion of experiments or simulations and some other advantages/disadvantages. Special focus has been put on those studies that apply these methodologies to humans, animals or biological systems. In the authors' opinion, the inclusion of such systems in the estimation loop hinders the design/performance of the observers, demanding particular attention. All this information, gathered in a feature table, is very useful to get a complete, rigorous and objective view of the revised topic. Finally, the research questions initially formulated are answered trying to provide a full and objective perspective of the topic.

This paper is organised as follows. Section 2 presents the preliminary concepts and the description of the different phases of the SR. The report of the systematic review is given in Section 3. Finally, the conclusions are drawn in Section 4.

2. Preliminary Concepts

A proper bibliographic review appears to be the necessary first step for every research, aiming to get deep insight into the state of the art to understand how it has evolved over the years and at what point it is nowadays.

This paper intends to bring the methodology of systematic reviews to the field of automation and control, using as guides published SRs in other areas of the literature, mainly social sciences and software engineering [1,6–8,13].

Typically, a systematic review of the literature consists of three well-defined sequential phases: The planning, the conducting and the reporting, as shown in Figure 1. In the next subsections, we will adapt this methodology to the peculiarities of our field.

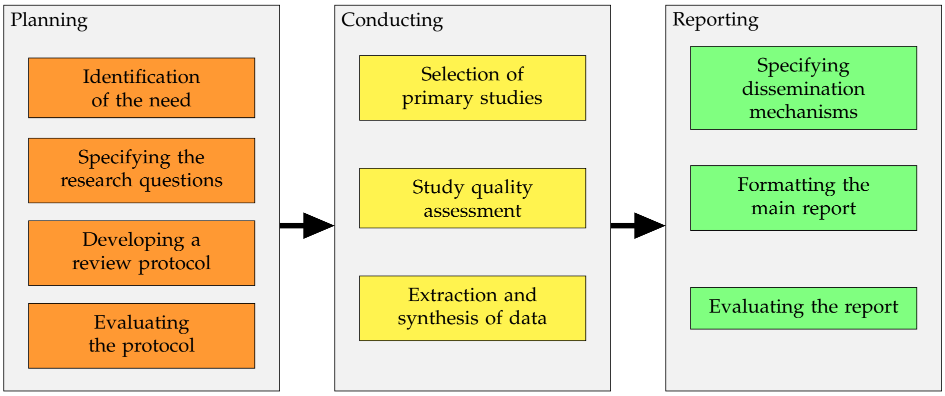

Figure 1. Phases y sub-phases of the systematic review [1].

2.1. Description of Phase 1: Planning the Review

The first step is the planning, perhaps the most important because it is the basis of the whole review. It is divided into four actions and it begins with the identification of the need for a systematic review. The researchers should identify existing systematic—which are almost inexistent in our field—and traditional reviews on the topic and ensure if it is worth undertaking the review.

The most important part of any SR is the formulation of one or more specific questions to which the SR expects to respond. As it is explained in [1], a right question should be meaningful to both practitioners and researchers. An adequate question should suggest modifications or increase the confidence on the current practice. A correct research of what we want to look for is fundamental for a targeted research, eliminating redundant information.

There are some guidelines for the formulation of the research questions in the medical field [14] or software engineering [1], but none on automation and control. It has been suggested to use the PICOC criteria (population, intervention, comparison, outcome, context) to frame research questions in social sciences [15] and in computer science [1]. Next, we make a reflection on how these criteria can be particularized to the automation and control sciences:

Population: The target population could be very varied:

- An application area, such as, solar fields, traffic systems, biological systems or smart grids.
- A particular description of a dynamical system, such as, linear vs nonlinear differential equations, state-space vs transfer functions, with or without noises or disturbances, uncertainty models, centralised vs distributed, etc.
- A well-described framework, such as, fault detection, formation control, networked control systems, system identification, etc.
- A specific course, module, group of students, etc.
- A given technology or equipment, as for instance an autonomous car, a chemical plant, a robotic arm or a drone.

Even, the population could consist of a combination of the mentioned items.

Intervention: The intervention is the particular automation and control methodology/algorithm/technology that addresses a specific task. For instance, it could be a model predictive control algorithm, a methodology for modeling robotic systems or a technology for performing hardware-in-the-loop simulations.

Comparison: It is the particular automation and control methodology/algorithm/technology that serves as comparison. For instance, distributed methodologies could be compared to centralised ones or linear controllers could be compared with standard PID controllers.

Outcome: These are factors of importance to practitioners and researchers that the proposed intervention achieves. This might be difficult to make precise, because there does not exist a normalisation of the outcomes of the studies in the control community. This drawback, which is also common for computer scientist, does not appear in social sciences, since their outcomes follow certain rules.

Some standards that usually appear in our field are: Qualitative/quantitative performance, rejection of disturbances/noises, reliability, resiliency to attacks, robustness against uncertainties in the models, computational complexity, communication needs, energy requirements or fulfilment of real-time needs.

Context: This is the context in which the comparison takes place. In this field, researchers make use of experiments or simulations to make comparisons with available interventions. Hence, some possible criteria could be: The presence/absence of a comparison, numerical vs applied simulations, field experiments, etc.

Please note that some of the previous criteria, such as outcome or context, are general and, therefore, equivalent to other fields. We have included them here in order to present a self contained document. Moreover, several examples, with standard keywords, have been provided to help the potential reader in the application of this criteria to automation and control.

Once the research questions have been formulated, the next step consists in developing and, later, evaluating a protocol. The protocol mainly serves to reduce the partiality of the study, defining clearly and precociously how to conduct the entire process of the systematic review, with every situation and norm to be followed in each phase and sub-phase [1,13,15]. In bio-sciences, the protocol is sometimes registered in a prospective register, such as PROSPERO (https://www.crd.york.ac.uk/prospero/). However, these kinds of registers do not exist in the automation and control field.

A protocol is usually organised in three main parts, namely, introduction, methodology and a brief discussion. The introduction presents the background and context of the particular area, stating the need and aims of the review, with the research questions.

The methodology should be based in a predefined standard guide, such as the PRISMA guidelines for SRs [9]. Based on those guidelines, the methodology should include, at least, the following items:

- Search strategy, that is, the key terms for the search, normally written as a Boolean function. In addition, it must be stated the sources that are to be searched to find the studies, such as digital libraries, specific journals and conference proceedings and the databases that include the contents of those sources.
- The inclusion and exclusion criteria for the studies.
- The particular procedure to be followed for the selection of primary studies. In particular, it should be mentioned the number of researchers that will evaluate the documents and the way in which a possible disagreement will be resolved.
- Assessment of risk of bias using, if possible, a standard method, such as the Cochrane guidelines [16].
- Strategy for data extraction, clearly identifying the information that is going to be gathered from the included primary studies.

It is a common practice in medicine to submit the protocol to peer review. In automation and control, it could be interesting to submit the protocol to a peer-reviewed conference which a certain impact, such us the CDC, ACC, IFAC WC or ECC. This could serve as a good evaluation of the protocol. In addition and since SR are almost inexistent in automation and control, the review protocol could be evaluated by an independent expert in bio-sciences or software.

Particular Features for the Methodology in Automation and Control

In this section, we will provide some notes concerning the methodology in the automation and control field.

Initially, the search begins by defining the Boolean function, which is nothing more than an extraction of keywords, joined by the supported operators, Booleans or not, from the different databases. We can also define it as a string with the most important words and synonyms extrapolated from the initial research questions. At this point, it is worth revising several survey papers and key studies in the field to find all the possible terminology associated to the research questions.

The next step is to appropriately choose the databases best suited to the topic of investigation, making sure to get a good coverage of the most important publishers. From the authors' point of view, in automation and control, the most important databases to be considered for a review are presented in Table 1. According to the information that these databases put in proportion (https://webofknowledge.com/; https://dl.acm.org/; https://ieeexplore.ieee.org/; https://www.scopus.com/; https://www.sciencedirect.com/; https://link.springer.com/; https://onlinelibrary.wiley.com/), most of the magazines and journals in automation and control and also the main conferences in this area, are published by publishers whose content appears in those databases.

Table 1 uses some acronyms to indicate the search fields. The most common searches are the one that covers the fields of abstracts, titles and keywords of the paper, labeled with $(A + T + K)$. Other characteristics are also included in Table 1, such as the number of maximum citations that can be downloaded at a single step, the format in which the citations can be downloaded, whether the downloads include the abstract or not, the Boolean operators that can be used (each database uses its own characters and Boolean operators) and the maximum number of terms allowed in the search string. Furthermore, there are two ways to perform the search in the databases: A structured advanced search (automatic) and a manual search by writing suitable commands (manual). In general, the last one let us perform more complex searches.

Table 1. Some of the most important databases in automation and control: A = abstract, T = article title, K = keywords, F = full text.

Databases	Search Fields	Manual or Automatic Search	Supported Operators	N^o Terms Supported	N^o Maximum Download	Citations Format	Download with "abstract"
Web of Science	A+T+K, T, F	Both	AND, OR, NOT, NEAR, (), *, ""	Not specified	50 citations	bib, RIS, CSV	YES
IEEE Xplore	A+T+K, A, T, K, F	Both	AND, OR, NOT, NEAR, (), *, ""	Only 40	2000 citations	bib, RIS, CSV	YES
ScienceDirect	A+T+K, A, T, K, F	Both	AND, OR, AND NOT, (), *, ?, "", {}	Not specified	200 citations	bib, RIS, Text	YES
ACM Digital Library	A+T+K, A, T, K, F	Both	AND, OR, NOT, (), ""	Not specified	2000 citations	bib, RIS, CSV	NO
Scopus	A+T+K, A, T, K, F	Both	AND, OR, AND NOT, *, ?, "", ()	Not specified	2000 citations	bib, RIS, CSV, Text	YES
SpringerLink	T, F	Automatic	AND, OR, NOT, "", ()	Not specified	2000 citations	CSV	NO
Wiley Online Library	A, T, K, F	Automatic	AND, OR, NOT, "", *, ()	Not specified	20 citations	bib, RIS, Text	YES
Google Scholar	T, F	Automatic	AND, OR, NOT, "", ()	Not specified	1 citation	bib, RIS	NO

Another important step of the SR is the establishment of the inclusion and exclusion criteria, which are fundamental in the selection process of the papers. Each candidate study, in order to move to the next stage, must include all inclusion criteria and must not present any of the exclusion criteria. The criteria, as indeed every step of the review, must be very clear, because the selection of primary studies is carried out by two people at the same time, who evaluate each work separately. In order to be included in the SR, the primary study must be accepted by both reviewers. In medicine or psychology, this evaluation is normally done by reading Title and Abstract. However, as it has been discovered by conducting this SR, titles an abstract in automation and control and other engineering fields are seldom normalised and, unluckily, sometimes they do not contain the necessary information to perform the evaluation. In those cases, the reviewer must read the full text. In the case of disagreement, a third person will decide whether to include it or not. This is a well-extended practice in SRs that can be inherited here.

The last points to consider are the study quality assessment checklist and the data extraction strategy. As we have already seen with other aspects of the SR, there does not exist a quality checklist to assess the individual studies in our field, so the reviewers could opt between modifying and adapt those found in the bio-science/social science literature or discarding this step.

Finally, for the data extraction, the following list of items is suggested. When extracting the data from the selected papers, among the characteristics that could be extracted, in general there are:

- Basic information: Authors, year of publication, title, etc.
- Field of application or study subjects or study type of each paper.
- Particular information related to the application context.
- Tools used.
- Test/experiment/simulation.
- Limitations and advantages.

2.2. Description of Phase 2: Conducting the Review

Once the precise research questions have been established, the appropriate databases have been chosen, the Boolean function has been defined and the inclusion and exclusion criteria have been set, we are ready to move on to the second block of the SR, presented in the Figure 1, which basically includes the selection of primary studies, study quality assessment, extraction and synthesis of data.

In order to guide this process, an international group of experts has developed the PRISMA method: A framework for the realisation of SR [9], which consists of 27 points and a flow diagram (see Section 3) that summarises the selection process.

At this point, the reviewers are faced with a great quantity of results, coming from the different databases used. The first filter to be applied, which is often included directly in the database, is the elimination of gray literature, which includes books, book chapters, poster presentations, reviews, surveys and doctoral theses that usually give rise to a journal article. In conclusion, we will include only original works that have gone through a peer-review process. It is of a crucial importance to use a tool to eliminate the duplicates, since the databases in automation and control share part of their content.

Then, the obtained primary studies will be evaluated by the reviewers (normally two people, as explained before) following the predefined protocol and applying the inclusion and exclusion criteria. This step will provide us the list of selected primary studies to be included in the SR.

In order to improve the list of studies, it is a good practice at this stage to contact the authors of the selected papers and check their bibliography to see if any possible paper has escaped the initial search. These additional papers will be included in the list of selected primary studies under the name of additional records identified through other sources (see Section 3). In the event that many items were found that were not included in the first list of studies, it is advisable to restart the SR, following the PRISMA procedure again.

The quality of the different works is evaluated using the tool presented in this subsection. For this paper, we have developed a very simple checklist that can be used to assess the quality of the papers included in the SR, see Table 2.

Table 2. Checklist for quality assessment.

	Question	Score
Q1	Is the problem presented clearly?	Yes/Partially/No
Q2	Is the methodology used presented clearly?	Yes/Partially/No
Q3	Are there any limitations and/or restrictions?	Hard/Soft/No
Q4	Is there a discussion of the results?	Yes/Partially/No
Q5	Does it answer all the questions originally formulated by the SR?	Yes/Partially/No
Q6	Has it been cited by many authors?	Cites/Year
Q7	Has it been published in a journal or conference proceeding?	Journal/Conference

For the extraction and synthesis of the data of each selected paper one can resort to different ways to re-organise the information, such as a narrative synthesis, a concept maps or a table of characteristics. In the authors' opinion, the latter is, perhaps, more useful in automation and control, since the reader (practitioner or researcher) will easily see the information collected from the studies and will be able to extract his/her own conclusions. These tables, in addition to standard information such as authors and year of publication, present the information that has been previously stated in the protocol. They summarise in a visual way the features and peculiarities of each work.

The data extraction procedure should be performed by more than one reviewer, following a similar protocol than the one established for the inclusion of primary studies. If this cannot be done, at least, some methods should be introduced to check that the data are being extracted correctly. For instance, if a PhD is conducting this phase, the supervisor could randomly pick some of the studies and extract the features, to make a comparison with the data extracted by the student. In general, the risk of bias or rigorousness can be reduced by including more people in any decision.

2.3. Description of Phase 3: Reporting the Review

The conclusive part of the SR concerns the preparation, reporting and dissemination of all the results obtained, that is the documentation of the extracted data. A critical and objective analysis of the salient features of the works will be presented, comparing the results obtained and reasoning on them.

In order to disseminate the results, there are different options, which should be taken into account depending the target audience: Academic journals/conferences, practitioner-oriented magazines, posters, web pages or direct communication. The choice of the dissemination mechanism directly affects the format in which the SR will be reported. The structure and contents of this report are usually normalised in other areas [1].

The evaluation of the report will be done as an unavoidable step when it is submitted for publication to a peer-reviewed journal.

3. Report of the Systematic Review

This section presents the report of the systematic review on distributed estimation techniques applied to cyber-physical systems, that follows the structure presented in [1].

3.1. Background

Cyber-physical systems (CPS) integrate computing and communication capabilities with monitoring and control of entities in the physical world. These systems are usually composed by a set of networked agents including sensors, actuators, control processing units and communication devices [17], as shown in Figure 2.

One of the difficulties presented by the CPSs, which derives from their inherent complexity and heterogeneity, is the need to know or at least have a reliable estimate of the variables of the complete system, both to monitor and supervise it and to be able to control it correctly. Given that the entities that are part of a CPS have in general different sensing, computing and control capacities, as well as access to certain local information of the complete system, depending for example on their location, it is necessary to develop coordinated strategies to be able to supervise the system in a distributed way from the devices that are integrated into it. This coordination requires some sort of communication between the agents.

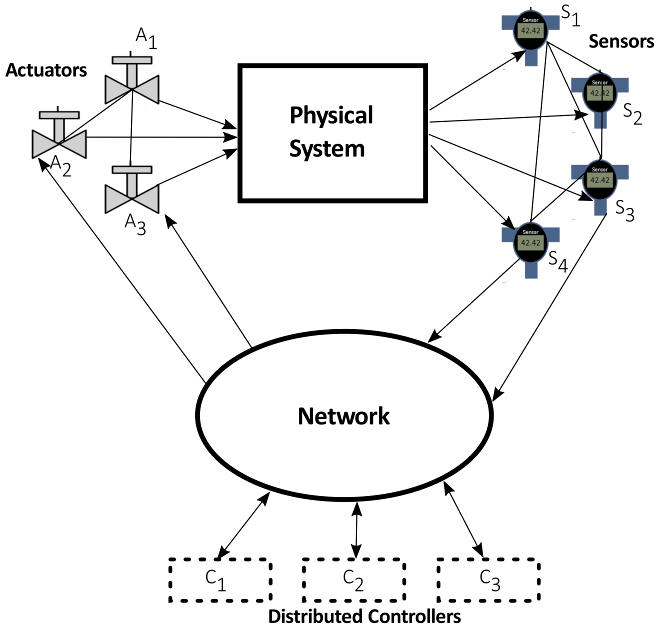

Figure 2. The architecture of cyber-physical systems [17].

For the distributed estimation of the state on sensor networks there are various algorithms proposed in the literature that constitute extension of well-known classical estimators.

The first family of techniques, referred to as Kalman filters, uses a series of measurements observed over time, containing statistical noise and other uncertainties to identify the hidden state, not measurable [18]. In particular, the Kalman filter operates by propagating the mean and covariance of the state through time. In the last decades, it has been applied to distributed systems with great success, see for instance [19–21].

Another approach to state estimation is the Bayesian filter, which produces recursively an estimate for the targets joint probability density, given the current information [22]. It is a statistical approach to estimate, in particular for the systems that are highly nonlinear. It is a probability-based estimator [23]. Some extensions to distributed frameworks in combination with particle filters can be found in [24–26].

An additional noteworthy estimation technique is the Luenberger observer. It estimates the hidden internal state not measurable of a linear dynamic system from the measurements of the input and output of the system [27]. Recently, many authors have proposed different formulations of distributed Luenberger observers [28–30].

Further techniques exist and have found application for distributed plants. For instance, adaptive observers model the relationship between signals in real time in an iterative way, changing their coefficients according to an adaptive algorithm [31]. H_∞ filters [23] are mainly used for multi-variable systems with couplings between the channels and with systems that have model uncertainty, see [32]. Sliding mode observers, with important measurement noise resilience, have been applied in [33]. Finally, set-membership observers are mainly used when noises and disturbances are bounded, in such a way that no statistical description is required, see [34].

3.2. Review Questions

The goal of this SR consists in locate and compare the different distributed estimation techniques that have been applied to cyber-physical systems. In pursuing this goal, the next research questions have been formulated:

RQ.1: What distributed estimation techniques are used in cyber-physical systems, heterogeneous systems or system of systems?

RQ.2: What are the limitations and advantages of the different techniques?

RQ.3: What are the fields of application in which these techniques are used?

RQ.3.1: In applications that include humans, animals or biological systems, which estimator obtains better results?

Since the term cyber-physical systems is kind of new, we have included the more general terms heterogeneous systems and system of systems, which sometimes are used to refer a CPS. Using the proposed PICOC criteria defined in Section 2, these research questions are described by:

Population: Cyber-physical systems, heterogeneous systems or system of systems.
Intervention: Distributed estimation.
Comparison: No additional criterion.
Outcome: Type of design (decentralised/centralised), exchanged information, communication protocol, another advantage/disadvantage.
Context: No additional criterion.

We have left the "comparison" and "context" criteria empty in order to not further restrict the search and so that more candidates' papers are screened.

3.3. Review Methods

The following subsections are mainly based on the protocol presented in [35]. However, some minor modifications have been introduced since it was published. These modifications will be mentioned when appropriate.

3.3.1. Data Sources and Search Strategy

We have chosen the databases presented in Table 3, namely, IEEE Xplore Digital Library, Web of Science, ScienceDirect, ACM Digital Library and Scopus. The reason for this choice is twofold. Firstly, we have excluded those databases that did not allow to make the search in the abstract, title and keywords, as detailed in Table 1. Secondly, the content of these databases covers the main publishers in automation and control, as Table 3 illustrates in a graphical way.

The time interval considered for the search is wider than the one in [35], going from 01/01/1990 to 12/09/2019.

Table 3. Databases coverage with respect to the content of the publishers [35].

	IEEE Xplore	**ACM Digital Library**	**Scopus**	**Web of Science**	**Science Direct**
IEEE	■	■	■	■	
IET	■				
Pegamon Elsevier		■	■	■	■
Elsevier Science		■	■	■	■
Wiley Blackwell	■		■	■	
Taylor and Francis		■	■	■	
Springer		■	■	■	
SIAM Publications		■	■	■	
Oxford University Press		■	■	■	
Korean Inst. Electrical Eng.			■		
Sage Publications		■	■	■	
ASME			■		
Microtome Publications		■			

The Boolean function for the search includes now some additional terms on top of the one in [35], since we discovered that some key primary studies were not screened. The Boolean function is, then:

(Estimator OR Estimation OR Filter OR Filtering OR Observer OR Observability OR Sensing) AND
("Cyber Physical System" OR "Human in the loop" OR "Human Robot" OR "System of systems" OR "Heterogeneous System" OR "Human Machine" OR "Heterogeneous Multiagent System" OR "Humanoid Robot" OR "Animal Robot" "Biological System" "Physical System" "Physically-aware Engineered Systems") AND
(Distributed OR Decentralised OR Decentralised OR "Sensor Fusion" "Multi Sensor")

The first and third block refers to the Intervention. Note that similar terms must be included if we want to be sure that all the studies proposing distributed estimation techniques are going to be considered. The reader may find strange that the terms decentralized/decentralised or Sensor fusion appear in the search string when the proposed research questions clearly avoid them. The reason is that we have discovered that some authors use those names when they are proposing a distributed estimation technique.

In what respect to the population, the second block includes a set of key terms that are found in the literature for applications similar to those in which the SR is interested. These terms have been found by reading some survey papers in the field, with the expertise of the authors and by several post refinements after making trial searches.

3.3.2. Study Selection

The guidelines presented in the protocol [35] have been followed. Two reviewers evaluate each work separately and, to be included, the primary study must be accepted by both reviewers, leaving to a third reviewer the final decision in case of disagreement. We have used the PRISMA method [9] to drive this sub-phase.

In the screening step, the inclusion and exclusion criteria are applied to the title and abstract. Then, with the preliminary candidate studies, we will perform a full-text reading to finally discard those studies that did not satisfy all the inclusion criteria.

3.3.3. Study Quality Assessment

In this secluded is applied the checklist for quality assessment, show in the Table 2 to the papers selected for the SR, to highlight the quality through the different questions.

3.3.4. Data Extraction and Synthesis

This SR will summarise the extracted data from the selected primary studies using a feature tables. The data that are going to be extracted from the papers and that, hence, will be included in the tables are:

- Year of publication.
- The sort of estimator used, such as a Kalman filter, a Luenberger observer, a Bayesian filter or any other.
- The application, that is, what kind of dynamical system the estimator has been applied to, such as biological systems, structural health monitoring, CPS under some kind of cyberattack and so on.
- The inclusion of simulations and/or field experiments that demonstrate the effectiveness of the used estimator.
- The estimation objective, which indicates whether the dynamics to be estimated corresponds to the whole state vector or just a partial state vector associated with a local dynamics of each subsystem.
- The design of the proposed estimator, whether it is made in a centralised or a decentralised way. Please remember that the implementation must be decentralised.
- The information that needs to be exchanged between the agents. Two aspects are mentioned here: The size of the packets to be transmitted (using state vector (n) and output or sub component of the state (r) as a reference); the frequency at which those packets must be sent, distinguishing

between those estimators that require consensus steps between two consecutive sampling times and those estimators that run at the same rate as the plant.
- The communication protocol. We are not interested in the particular protocol, such as WiFi or ZigBee, but on the way each agent relates with the others. In particular, we will annotate whether the estimation algorithm requires all-to-all communication or just communication with neighboring agents. While there are other options, such as gossip or scheduled communication, no primary studies have been found to suit those categories.
- Other advantages/limitations that the authors of the primary studies mention or the reviewers discover. This feature is the only one that is subjective. However, we think that useful information that is not collected in the other features can be added at this point.

The data will be extracted by two reviewers to reduce the bias, going for a third one in case of disagreement. For the last features, both reviewers must agree on the selected advantage/limitation.

3.4. Included and Excluded Studies

The inclusion and exclusion criteria chosen for the selection of papers are shown in Tables 4 and 5, respectively. We have slightly relaxed the criteria compared to the protocol in [35]. For instance, the SR now accepts papers which do not present simulations or experiments or with a length shorter than three pages.

The selected criteria ensure that the search is focused on the chosen topic. For a paper to be included, it must satisfy all the inclusion criteria and none of the exclusion criteria. As mentioned in the introduction we are interested in those heterogeneous systems that have a certain dynamic and that incorporate a physical and a cybernetic part. Furthermore, the estimators must interchange some form of information with other agents.

Table 4. Inclusion criteria.

• Full paper available online (through search engines or by contacting the authors)
• Use or propose a distributed estimationtechnique on cyber-physical systems, heterogeneous systems or system of systems or make specific reference to humans, animals or biological systems
• Use a distributed estimator with some sort of communication between local estimators
• The system to be estimated must have dynamics

Table 5. Exclusion criteria.

• Secondary studies and gray literature
• Non-English written papers
• Duplicated studies
• Studies clearly irrelevant to the research
• Focused only on control

The number of papers obtained by launching this Boolean function in the chosen databases, in the established fields were 2848, see Table 6. With the mentioned modifications in the protocol the number of candidate studies has grown from 1788 to 2848, that is, an increment above 60%. The PRISMA complete flowchart is shown in Figure 3.

Table 6. Studies obtained by each database.

Database	Studies
Web of Science (WoS)	571
IEEE Xplore (IEEEX)	919
ScienceDirect (SD)	51
ACM Digital Library (ACM)	525
Scopus	782
	2848

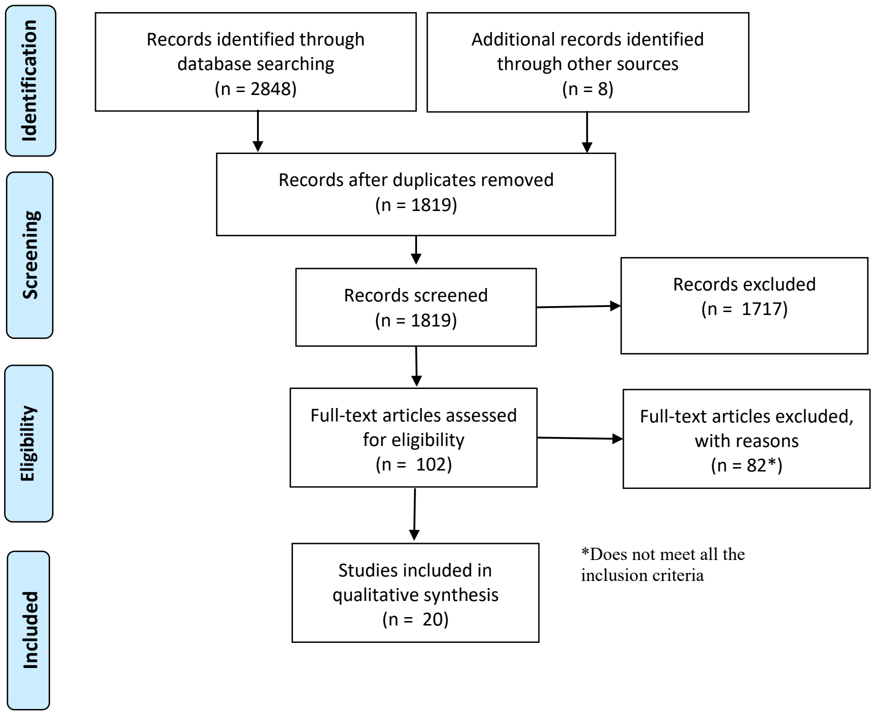

Figure 3. PRISMA (preferred reporting items for systematic reviews and meta-analyses) flowchart.

In this flowchart, in addition to the studies found in the aforementioned databases, those identified through other sources are specified, for example by contacting the authors and revising the bibliography of the selected papers. At this point the duplicates are removed, which are more than 1000 for our particular case, using an appropriate reference manager, such as Mendeley.

After the screening phase, the remaining studies are far less than the large quantity we had at the beginning: From the initial 2848 works, 102 papers remains. However, after a full-text reading, 82 papers were discarded. Finally, 20 papers have been found. In spite of the low percentage of selected papers (20 out of 2800), the analysis of these 20 papers indicates that they were an enough number of documents to identify interesting research gaps and conclusions.

3.5. Results

The quality of the selected papers have been assessed, obtaining the results depicted in Table 7.

The data extracted from the papers have been included in different tables, namely Tables 8–11, each associated to a research question. In the following section, the data are analyzed and several conclusions are drawn.

Table 7. Checklist for quality assessment.

	Q1	Q2	Q3	Q4	Q5	Q6	Q7
[36]	Yes	Yes	No	Yes	Partially	27/2008	Conference
[37]	Yes	Partially	Soft	No	Yes	2/2010	Conference
[38]	Yes	Yes	Soft	Yes	Yes	1/2012	Journal
[39]	Yes	Partially	Soft	Partially	Yes	24/2012	Conference
[40]	Yes	Partially	Soft	Yes	Yes	17/2013	Conference
[41]	Yes	No	No	Yes	Yes	5/2013	Conference
[42]	Yes	Yes	No	Yes	Yes	46/2014	Journal
[43]	Yes	Yes	Soft	Yes	Yes	81/2015	Journal
[44]	Yes	Yes	Hard	Partially	Yes	3/2016	Conference
[45]	Yes	Yes	Hard	No	Yes	9/2016	Conference
[46]	Yes	Yes	Soft	Partially	Yes	5/2016	Conference
[47]	Yes	Yes	Soft	Partially	Yes	25/2016	Conference
[48]	Yes	Yes	Soft	Yes	Yes	47/2016	Journal
[49]	Yes	Partially	Soft	Partially	Yes	2/2017	Conference
[50]	Yes	Yes	Soft	Partially	Yes	01/2017	Conference
[51]	Yes	Yes	No	Yes	Yes	14/2018	Journal
[52]	Yes	Yes	Hard	Yes	Yes	38/2018	Journal
[53]	Yes	Yes	Soft	Yes	Yes	1/2018	Journal
[54]	Yes	Yes	No	Yes	Yes	1/2018	Conference
[55]	Yes	Yes	Soft	Yes	Yes	13/2018	Journal

3.6. Discussion

The systematic review is completed by carrying out the discussion. Firstly, the principal findings will be clarified and, later, an analysis on the strengths and weaknesses of the SR will be performed.

3.6.1. Principal Findings

In the following, we provide a clear and detailed answer to each of the research questions that were exposed at the beginning of the review.

RQ.1: What distributed estimation techniques are used in cyber-physical systems, heterogeneous systems or system of systems?

The distributed estimation techniques used in the selected papers are varied, as Table 8 shows. Mainly they can be divided into the following groups:

- Adaptive observer, used in [46] for multi-agent systems, in [48] for leader–follower systems and in [55] for heterogeneous multi-agent system.
- Bayesian filter, also used in many areas, such as collaborative human–robot systems [36], joint attack detection and secure state estimation [51] or 3D upper body tracking, with a combination of annealing particle filter and belief propagation inference [38].
- H_∞ filter, which has been applied for the detection of biasing attacks on distributed estimation networks [45] and for the joint attack detection and secure state estimation [52].
- Luenberger observer, used in [40] for CPSs affected by adversarial attacks on the sensed and communicated information, in [42] for detecting and isolating multiple sensor faults, in [44] for the simultaneous estimation of the state and attack, in [53] with a secure pre-selector, in [47] for the state estimation in networks subject to adversarial attacks.
- Kalman filter, which has been used in various fields of application, such as fault detection and isolation for systems of systems [37], security of the state estimation in power systems [39], for attack detection in [54], multi-robot tracking [41], monitoring industrial CPSs [43] or estimation of the biofilm growing process in a biological system [50].

Table 8. Feature table. Estimation technique and application.

Cite	Year	Estimator Used	Application
[46]	2016	Adaptive observer	Heterogeneous multi-agent system
[48]	2016	Adaptive observer	Heterogeneous multi-agent system
[55]	2018	Adaptive observer	Heterogeneous multi-agent system
[36]	2008	Bayesian filter	Heterogeneous multi-agent system
[51]	2017	Bayesian filter	Attack detection and secure estimation
[38]	2012	Particle filter + Belief Propagation inference	3D Upper body pose estimation
[52]	2017	H_∞ filter	Attack detection and secure estimation
[45]	2016	H_∞ filter	Attack detection
[49]	2017	Luenberger observer and H_∞ filter	Attack detection
[40]	2013	Luenberger observer	Secure estimation
[47]	2016	Luenberger observer	Secure estimation
[42]	2014	Luenberger observer	Fault detection and isolation
[44]	2016	Luenberger observer	Attack detection and secure estimation
[53]	2018	Luenberger observer with secure pre-selector	Attack detection and secure estimation
[37]	2010	Kalman filter	Fault detection and isolation
[39]	2012	Kalman filter	Secure estimation
[41]	2013	Kalman filter	Heterogeneous multi-agent system
[43]	2015	Kalman filter	Monitoring industrial CPSs
[50]	2017	Kalman filter	Biological system
[54]	2018	Kalman filter	Attack detection

It should be mentioned the paper [49], which presents two different estimation techniques: The attack estimation is carried out by means of a H_∞ filter, whereas the state estimation, considering the attack previously estimated, is done with a Luenberger observer.

Finally, it deserves to be remarked that some estimators have not been found to be applied to CPSs, such as sliding mode observers or set-membership observers.

RQ.2: What are the limitations and advantages of the different techniques presented in the different papers?

This question is focused on the limitations and/or advantages that have been found in the selected papers and shown in the Table 9. The answer to this question is rather complex and wide, because, when studying a paper, it is not easy to extract the limitations and/or advantages, because it is sometimes a subjective aspect. In the following, we will present some reflections and considerations extracted from the data.

Let us first pay our attention on the design of the estimators. Whereas most of the studies present design methods that can be implemented in a decentralised way, there are some papers in which the estimators need to be design in a unique centralised step. This is the case of [45,52], where a unique linear matrix inequality must be solved to find the observer gains. In [44] the authors require to solve decentralised Lyapunov matrix equations to ensure that both the state and the attack is estimated. However, those equations require global information that, in general, is not available in every location, such as the output matrices and Luenberger observer gains of every estimator.

It is worth mentioning that most authors have used H_∞ filters for attack detection, see [45,49,52]. In order to ensure a given H_∞ bound γ, all these papers require to solve centralised LMIs. In fact, there exists no study that has solved this problem using a pure decentralised approach. Other options available are the papers [44,51]. The former, based on a Luenberger observer, is adequate when the system is described as a set of, possibly nonlinear, subsystems. The latter uses a Bayesian filter to estimate the complete state of the plant.

Table 9. Features table. Limitations and advantages according to a given criteria. Color code: Green = desired, yellow = intermediate, red = undesired.

Cite	Estimator Used	Experiment or Simulation	Estimation Objective	Design	Exchanged Information	Communication Protocol
[46]	Adaptive observer	Simulation	Local state	Decentralised	Estimated state vector (n) + adaptive system matrix (n*n), same rate as the system	Neighbourhood
[48]	Adaptive observer	Simulation	Local state	Decentralised	Estimated state vector (n) + adaptive system matrix (n*n), same rate as the system	Neighbourhood
[55]	Adaptive observer	Simulation	Local state	Decentralised	Estimated state vector(n) + adaptive system matrix (n*n), same rate as the system	Neighbourhood
[36]	Bayesian filtering	Experiment	Complete state	Decentralised	Estimated state vector (n) and output (r<n), same rate as the system	Neighbourhood
[51]	Bayesian filter	Simulation	Complete state	Decentralised	Estimated state vector (n) consensus between sampling instants	Neighbourhood
[38]	Particle filter + Belief Propagation inference	Experiment	Local state	Decentralised	Estimated state vector (n) * Number of particles (N), at a rate N_{BP} higher than the rate of the system	Neighbourhood
[52]	H_∞ filter	Simulation	Complete state	Centralised	Estimated state vector (n), same rate as the system	Neighbourhood
[45]	H_∞ filter	None	Complete state	Centralised	Estimated state vector (n), same rate as the system	Neighbourhood
[49]	Luenberger observer and H_∞ filter	Simulation	Local state	Decentralised	Estimated state vector (n), consensus between sampling instants	Neighbourhood
[40]	Luenberger observer	Simulation	Complete state	Decentralised	Estimated state vector (n) and output (r<n), same rate as the system	Neighbourhood
[47]	Luenberger observer	None	Complete state	Decentralised	Estimated state vector (n), same rate as the system	Neighbourhood
[42]	Luenberger observer	Simulation	Local state	Decentralised	Subset of the estimated state vector (r<n), same rate as the system	Neighbourhood

Table 9. *Cont.*

Cite	Estimator Used	Experiment or Simulation	Estimation Objective	Design	Exchanged Information	Communication Protocol
[44]	Luenberger observer	Simulation	Local state	Centralised	Estimated state vector (n), same rate as the system	All-to-all
[53]	Luenberger observer with a secure pre-selector	Simulation	Local state	Decentralised	Estimated state vector (n), same rate as the system	All-to-all
[37]	Kalman filter	Simulation	Complete state	Decentralised	Estimated state vector (n) and residuals (n), same rate as the system	All-to-all
[39]	Kalman filter	Simulation	Complete state	Decentralised	Estimated state vector (n), consensus between sampling instants	Neighbourhood
[41]	Kalman filter	Both	Local state	Decentralised	Estimated state vector (n), same rate as the system	All-to-all
[43]	Kalman filter	Simulation	Complete state	Decentralised	Estimated state vector (n), same rate as the system + augmented output vector (n) and augmented noise matrix (n*n), tree-based broadcasting + augmented output vector	Neighbourhood
[50]	Kalman filter	Simulation	Complete state	Decentralised	Estimated state vector (n), consensus between sampling instants	Neighbourhood
[54]	Kalman filter	Simulation	Local state	Decentralised	Estimated state vector (n) same rate as the system	Neighbourhood

Consensus algorithms have been vastly used in distributed estimation in general and in distributed estimation for CPSs in particular, see [36,37,39,40,43,45,47,49–52]. While the consensus methods are well known, it should be remarked that there are important differences in the way they influence the estimation algorithm. Mainly, we could distinguish between those consensus iterations that run at the same rate of the estimator [36,37,40,45,47,52] and those others that need to be executed many times (usually a large number of iterations, since consensus algorithms typically converge asymptotically) between two consecutive estimation steps [39,43,49–51]. Therefore, and despite the same word being used in the papers, enormous differences exist in what respect the information exchanged (see Table 10).

Table 10. Features table. Other limitations and advantages.

Cite	Estimator Used	Limitations	Advantages
[46]	Adaptive observer	Scalar gains. Measure the whole state	Do not require to know the system matrix. The consensus gains are dynamically chosen
[48]	Adaptive observer	Scalar gains.	Do not require to know the system matrix
[55]	Adaptive observer	Scalar gains. Leader's dynamics is required	Do not require to know the system matrix
[36]	Bayesian filter	Acyclic communication graphs	Moving sensors and targets. Collaboration between human and robots. Consider packet dropouts
[51]	Bayesian filter	Secure communication between fusion nodes. Scalar consensus gains	Nonlinear systems. Different kinds of attacks
[38]	Particle filter + Belief Propagation inference	Communication effort	Linear complexity according to the number of body parts
[52]	H_∞ filter	LMI centralised design. Require statistical information	Different kinds of attacks.
[45]	H_∞ filter	LMI centralised design	Local and consensus matrix gains Attacks on the estimator dynamics
[49]	Luenberger observer and H_∞ filter	No method for design the observer gains. Centralised detection based on H_∞ filter. Communication effort	Descriptor system. Attack policy on sensor signals
[40]	Luenberger observer	Direct state observations. Full rank output matrix. Scalar consensus gains	Robust against compromised communication
[47]	Luenberger observer	Constraints in the system matrix. Scalar consensus gains	Decoupling of observable and unobserval dynamics. Byzantine adversaries
[42]	Luenberger observer	Fusion center for fault isolation	Observer for Lipschitz nonlinear systems. Multiple fault detection and isolation. Structured fault sensitivity
[44]	Luenberger observer	Global information for design	Nonlinear descriptor systems. Neural network for uncertainty approximation
[53]	Luenberger observer with a secure pre-selector	Only out of sensors are manipulated arbitrarily by attackers	the exact secure state estimation is achieved in a pregiven finite time
[37]	Kalman filter	The consensus matrix gains are diagonal. There is no algorithm to design these gains	Distributed decision make without fusion center.
[39]	Kalman filter	Communication effort. Consensus constraints as in Olfati Saber[19]	Robust against false data injection
[41]	Kalman filter	The estimator is not presented formally	Moving sensors. Low computational requirements
[43]	Kalman filter	Communication effort	Two kinds of nodes: sensor and relay nodes
[50]	Kalman filter	Mono-variable system. Requires statistical information of the graph. Communication effort	Consensus under interferences, packet losses and different topologies
[54]	Kalman filter	Communication effort	There are no restrictions on the types of attacks

Consensus algorithms are used in those papers with several objectives. The most common application is for the agreement in the estimated state vector, see [37,39,40,45,47,52]. Another example is found in [49], where consensus is used for the residuals. The authors in [43,50] use the consensus because they need to estimate the output vector. Finally, the approaches in [36,51] incorporates a consensus algorithm to achieve an agreement in a probability density function.

Concerning the consensus gains that those algorithms use, in the vast majority of cases it consists in a scalar gain, as for example in [40,46–48,51,55]. In [37], a consensus matrix is proposed, but it is required to be diagonal matrix. Only the paper [45] uses a consensus matrix, but it is a unique matrix gain for every neighbor and it must be found after an LMI. Hence, it has been observed that none of the proposed studies have been able to use (and distributed design) different consensus gains for every neighbor.

To deepen the discussion concerning the required communication (see Table 10), it is noted that in those estimators based on the Luenberger observer, i.e. [40,42,44,47,53], the information exchanges between agents, take place at the same rate as the estimation algorithm. Moreover, the agents exchange the estimated state vector or a sub component of it. On the contrary, those approaches based on Kalman filters usually require a lot of information, as in [43], or consensus iterations between estimation steps, as in [39,50], with the consequent communication effort. A similar drawback appears in [38], where a lot of information must be sent between the particles of the filter between two consecutive sampling instants.

Distributed estimation techniques have been also applied to fault detection and isolation, see [37,42]. Both studies present distributed fault detection algorithms, for LTI systems [37] and for Lipschitz nonlinear systems [42]. It should be noted that, whereas in [42] a fusion center is required for fault isolation, the algorithm presented in [37] is able to provide distributed decisions.

Finally, it is worth mentioning the research developed in [36,41] for heterogeneous multi-agent systems. These studies consider a group of robots that are endowed, among others, with an estimation unit. These units have the objective of estimating the state (position, velocity orientation) of the associated robot and some target (a ball position, as in [41] and other robots' states, as in [36]). The presented estimation algorithms can be implemented in moving agents.

RQ.3: What are the fields of application in which these techniques are used?

Most of the applications found in the selected papers lie within the following four main categories (see Table 11):

- Heterogeneous multi-agent system: Different cases are considered in these studies in which there are different types of systems. In [36] a scalable collaborative human–robot system for information gathering applications, through a decentralized Bayesian fusion algorithm, is presented. The results of a collaborative multi-target search experiment conducted with a team of four autonomous mobile sensor platforms and five humans carrying small portable computers with wireless communication are presented to demonstrate the efficiency of the approach. In the paper [41], a multi-object, multi-sensor and cooperative tracking method using a Kalman filter is proposed for the Robocup Standard Platform League, where two teams of humanoid robots play soccer against each other.

It is worth mentioning that the documents [46,48,55] deal with the same application, that is, the synchronization of heterogeneous systems. All those papers propose the use of an adaptive observer, with different modifications, as will be mentioned next.

The exogenous signal representing the reference input to be tracked is assumed to be generated by a so-called exosystem as follows:

$$\dot{x}_0(t) = S_0 x_0(t), \tag{1}$$

with S_0 being a known constant matrix.

The agents are modelled as linear time-invariant systems described by:

$$\begin{aligned} \dot{x}_i(t) &= A_i x_i(t) + B_i u_i(t) + E_{xi} x_0(t) + E_{wi} w_i(t), \\ y_{mi}(t) &= C_{mi} x_i(t) + D_{mi} u_i(t) + F_{m_{xi}} x_0(t) + F_{m_{wi}} w_i(t), \end{aligned} \tag{2}$$

where for $i = 1, \ldots, N$, x_i, y_{mi}, u_i are the state, measurement output and input of the ith subsystem. External disturbances w_i are assumed to be generated by an independent linear system, that is, $\dot{w}_i(t) = Q_i w_i(t)$.

The authors in [46] propose a self-tuning observer to estimate the state of the leader from each agent. Then, using this information, they compute appropriate control inputs to achieve the synchronization between the states of the leader and followers.

The main novelty of [48] is that both the leader's and the follower's dynamics are assumed to be unknown. On the other hand, the synchronization problem is posed in [55] as a distributed optimal tracking problem, deriving inhomogeneous algebraic Riccati equations to solve it.

- Attack detection and secure estimation: Intense research has been done in these categories, with some papers tackling both challenges at the same time. They represent most of the applications encountered, even if in some papers it is only the attack detection, like in [45,49,54] and in others only the secure estimation, like in [39,40,47]. Only in [44,51–53] are both considered. Secure estimation is certainly among the most addressed topics in the reviewed articles. Perhaps the main difference between those papers is the typology of the attacks/attackers and the way the secure estimation is achieved.

False data injection attack: This is when a malicious adversary launches false data injection attacks at the physical system layer to intentionally modify the system's state and/or the measured output. From a mathematical point of view, false data injection attacks are usually modeled as additive disturbance or additive noise:

$$x^+ = \begin{cases} f_1(x,u,w), & \text{Under no attack} \\ f_2(x,u,w,a), & \text{Under attack} \end{cases}, \quad y = \begin{cases} h_1(x,v), & \text{Under no attack} \\ h_2(x,v,b), & \text{Under attack} \end{cases}, \tag{3}$$

with x, u, w, v being the state, input, external disturbance and measurement noise, respectively, and a, b the false data injection in the system dynamics or the measured output.

This is the case in [44], in which the attacks affects both the dynamics of a nonlinear descriptor system and the measurement output. This paper proposes a distributed robust approach using a Luenberger observer. Similarly, in [51], the attack detection-state estimation problem is formulated in the context of random set theory by representing the joint information on the attack presence/absence, on the system state and on the signal attack, in terms of a hybrid Bernoulli random set density, using a recursive Bayesian filter.

Several authors consider a simplification of the previous problem by assuming a linear time-invariant system, such as:

$$\begin{aligned} x(k+1) &= Ax(k) + Bu(k) + B_w w(k) + Ea(k), \\ y(k) &= Cx(k) + v(k) + b(k), \end{aligned} \tag{4}$$

where $x(k), u(k), y(k), w(k), v(k)$ are, respectively, the state, input, the measurement output, disturbances and the process noise at the k-th time step. The attack signals are $a(k), b(k)$.

In this line, [52] studies the situation in which the attacks only affects the system dynamics (i.e., $b(k) \equiv 0$). They propose an distributed H_∞ filter for attack detection and secure estimation. The attacks on the outputs are analyzed in [53,54] with a distributed Kalman filter in the former and a Luenberger observer in the latter. Finally, [49] considers a descriptor linear time-invariant system whose outputs can be compromised by false data injection attacks. The authors combine a Luenberger observer and an H_∞ filter to detect the attack and be resilient to its effect.

It is worth mentioning the work [45], which studies a different situation in which the attacks directly affect the estimator dynamics:

$$\dot{\hat{x}}_i(t) = Ax_i(t) + L_i(y_i(t) - C_i\hat{x}_i(t)) + K_i \sum_j (\hat{x}_j(t) - \hat{x}_i(t)) + f_i(t), \tag{5}$$

with $f_i(t)$ the signal attack to be detected using, in this case, a distributed H_∞ filter.

Jamming attack: This sort of attack pursues to block the wireless transmission channels between sensors and remote estimators, incurring in a possible packet loss or a partial degradation of the information. Therefore, it is considered a situation in which the sensors are not physically located near the agent, unlike the previous cases.

To model jamming attacks, the authors in [52] use the following formulation:

$$\hat{y}_i(k) = y_i^{attk}(k) + y_i^{comp}(k) + D_i v_i(k), \quad \forall i, \tag{6}$$

where the corrupted measurement $\hat{y}_i(k)$ that the remote estimator receives consists of two terms plus a noise:

$$\begin{aligned} y_i^{attk}(k) &= \theta_i(k) y_i(k), \\ y_i^{comp}(k) &= (1 - \theta_i(k)) \hat{y}_i(k-1), \end{aligned} \tag{7}$$

and specifically:

- $y_i^{attk}(k)$ stands for the attacked and manipulated measurement term. Signal $y_i(k)$ is the actual output measured by the sensor.
- $y_i^{comp}(k)$ represents the compensated measurement term corresponding to the lossy measurement $y_i^{attk}(k)$ caused by the attacker.
- $v_i(k)$ denotes the measurement noise experienced through the wireless channel.

The stochastic variable $\theta_i(k)$ takes values of 1 and 0, with $\theta_i(k) = 0$ representing the case of a jamming attack.

With the assumption of $\theta_i(k)$ being a Bernoulli distributed white sequence, with known expected value $E\{\theta_i(k)\} = \beta_i$, a measurement compensation unit is proposed in [52] for this kind of attack. It is based on a buffer that stores past data that are used in case of attacks.

To tackle the random jamming attacks, a refined measurement output model based on compensated measurements has been proposed and resilient estimators have been constructed.

Fake communications: with this name, we refer the situation in which the attacker is able to gain control of a communication link to substitute real packets or to inject extra packets when two agents or estimators interchange some sort of information. It is, therefore, an attack that takes place in the cyber layer. Secure estimators for this sort of attacks is presented in [49,51,54].

Denoting by $\mathcal{Z}_{i,j}(k)$ the information that agent i receives from agent j, fake communication are modeled in [51] as:

$$\mathcal{Z}_{i,j}(k) = \mathcal{Y}_{i,j}(k) \cup \mathcal{F}_{i,j}(k), \tag{8}$$

where

$$\mathcal{Y}_{i,j}(k) = \begin{cases} y_{i,j}(k) & \text{no attack} \\ 0 & \text{complete packet substitution} \\ \tilde{y}_{i,j}(k) & \text{packet modification} \end{cases},$$

and $\mathcal{F}_{i,j}(k)$ is the set of any fake packet originated by the attacker.

In particular, the paper [51] analyses a cluster-based network, wherein multiple cluster-heads receive data from remote sensors via non-secure links and exchange processed information neighborwise via secure links.

Fake communications are also considered in [49], in which the authors introduce a specific cyber-attack on the communication links between monitoring centres, in addition to false data injection sensor attacks. The novel Kullback-Liebler divergence based detector is used in [54] to capture the fake communications.

Fake agent: This is the case where either the attacker has gained control of an agent or the agent itself is the attacker. In both cases, the information that this agent sends to the rest of estimators can be compromised.

A trust-based mechanism is proposed in [39,40] to cooperatively detect the fake agent and reduce the impact of the information received from it, , in the first case through a Kalman filter, while in the second with a Luenberger observer. A similar version of the fake agent can be found in [47] under the name of Byzantine adversaries. In this case, the problem is analyzed using a distributed Luenberger observer based on subspace decomposition. This kind of Byzantine agent is given complete knowledge of the network and system dynamics and is allowed to deviate from the rules of any prescribed algorithm. Sufficient conditions for state estimation are provided in [47], relying on the construction of a directed acyclic graph. In this paper, the authors allow for the possibility that certain nodes in the network are compromised by an adversary and do not follow their prescribed state estimate update rule.

Two subsets of V (set of nodes) are created: R comprising of regular nodes and $A = V \setminus R$ comprising of adversarial nodes. They consider the Byzantine fault model where an adversarial node can arbitrarily deviate from the rules of any prescribed algorithm and can transmit different state estimates to different neighbors at the same time step. In addition, the adversarial nodes possess complete knowledge about the graph topology and the plant dynamics, i.e., an adversarial node knows the measurements of the normal nodes at every time step. They endow such privileges to the adversaries with the aim of providing resilience to worst-case behavior. This is known in the literature, as the f-total adversarial model.

Definition 1. *(Omniscience) A distributed observer achieves omniscience if* $\lim_{k\to\infty} \|\hat{x}_i(k) - x(k)\| = 0, \quad \forall i \in \{1, \ldots, N\}$, *i.e., the state estimate maintained by each node asymptotically converges to the true state of the plant.*

Definition 2. *(f-local set) A set* $C \subset V$ *is f-local if it contains at most f nodes in the neighborhood of the other nodes, i.e.,* $|N \cap C| \leq f, \forall i \in V \setminus C$.

Definition 3. *(f-local adversarial model) A set A of adversarial nodes is f-locally bounded if A is an f-local set.*

Considering the following system (Equation (9)):

$$\begin{aligned} x(k+1) &= Ax(k), \\ y_i(k) &= C_i x(k), \end{aligned} \tag{9}$$

the problem in [47], is to formulate a state estimation scheme so that

$$\lim_{k\to\infty} \|\hat{x}_i(k) - x(k)\| = 0 \quad \forall i \tag{10}$$

regardless of the actions of any f-locally bounded set of Byzantine adversaries.

- Fault detection and isolation (FDI), are found in [37,42]. In [37] a new algorithm is proposed for distributed fault detection and isolation, applicable to systems of systems based on Kalman filter. The mathematical formulation for a fault detection and isolation system with q faults presented in [37] is:

$$\begin{aligned} \dot{x}(t) &= Ax(t) + \Gamma w(t) + \sum_{k=1}^{q} \bar{F}_k \bar{\mu}_k(t), \\ y(t) &= Cx(t) + v(t), \end{aligned} \tag{11}$$

where x, y, w, v are the state, output, input and measurement noise vectors, respectively, of the system.

The authors assume that there is one target fault to be detected by every agent $i \in 1, \ldots, q$, denoted $\mu_1(t) = \bar{\mu}_i(t)$; the rest of the faults represent the nuisance fault μ_2, i.e., $\sum_{k=1}^{q} \bar{F}_k \bar{\mu}_k(t) = F_1\mu_1(t) + F_2\mu_2(t)$.

The main contribution of [42] is the design and analysis of a fault diagnosis methodology, with emphasis on the distributed isolation of multiple sensor faults that may affect the physical part of multiple interconnected cyber-physical systems, which may exchange sensor information related to the physical interconnections. This methodology builds upon a distributed Luenberger observer.

- Other applications: In this group, three particular studies not related to the previous groups were included. In [38], the authors propose a new approach for 3D upper body pose estimation, using a combination of an annealing particle filter and belief propagation inference. The work [43] is concerned with the distributed estimation problem, adopting a Kalman-like filter, for industrial automation over relay assisted wireless sensor networks. Finally, in [50] a biological system is considered. In this work, the authors present a framework for the use of a wireless sensor network as an estimator of the biofilm evolution in a reverse osmosis membrane so that effective solutions can be applied before the irreversible phase is attained.

Table 11. Features table. Fields of application of the surveyed studies.

Application	Studies
Heterogeneous multi-agent system	[36,41,46,48,55]
Fault detection and isolation	[37,42]
Attack detection	[44,45,49,51–54]
Secure estimation	[39,40,44,47,51–53]
Others	[38] 3D Upper body pose estimation [43] Monitoring industrial CPSs [50] Biological system

RQ.3.1: In applications that include humans, animals or biological systems, which estimator obtains better results?

While the review has been targeted at this kind of application, not many items have been found that include humans, animals or biological systems. Consequently, it is not possible to make real comparisons or to extract the best conclusions. For instance, no paper was found that includes animals in the application.

We must firstly mention [50], which uses a distributed Kalman filter for a biological system. In particular, the authors present a deployment of a wireless sensor network to estimate the biofilm evolution in a reverse osmosis membrane. They obtain nice results in simulation. However, in order to extract valuable conclusions, experimental validation is required.

Another paper that satisfies this requirement is [36]. It presents a coordinated network of humans and robots for state estimation using a Bayesian filter. Peer-to-peer collaboration between human–computer augmented nodes and autonomous mobile sensor platforms happens by sharing information via wireless communication network. The proposed method is tested with experiments, which show that improved results are obtained due to the human–robot collaboration.

3.6.2. Strengths and Weaknesses

This study presents several weaknesses, some that are typically common to all SRs and others that appear due to the inexistence of this kind of review applied to our field:

- With the aforementioned criteria, five digital databases have been chosen to include as many relevant papers as possible. However, all published papers on the topic cannot be analyzed, limiting the review conducted.
- Another possible weakness might be the inclusion and exclusion criteria adopted for selecting papers. For example, we have focused on papers published in English, but there might be relevant studies written in other languages.
- Many databases are not prepared for such an accurate research as the one described in Section 3.3.
- There exists no normalisation for the contents of abstract and title in control and automation journals and conferences, a problem shared with other fields, such as computer science. Moreover, although the keywords are sometimes normalised, they are not usually peer-reviewed. This makes it difficult to make a correct screened reading just title and abstract. Then, full text must be revised, so the time devoted in the very first phases of the review is really large. In contrast, the abstract of many social science papers must include, for instance, explicit reference to objectives, methods, results and conclusions; this eases the screening process.
- When extracting the data, it is often harder to compare two techniques or two aspects treated differently to in other sectors, such as medicine or psychology, where mainly studies and/or clinical data are compared. Then, we are forced to make a qualitative rather than a quantitative comparison (for instance, a meta-analysis). A possible solution to this weakness would be the formulation of benchmark problems, in which the same problem would be faced with different approaches, so as to be able to extract adequate quantitative conclusions.

On the other hand, this systematic review presents some strengths that must be pointed out:

- From the authors' knowledge, this is the first systematic review in automation and control, inheriting the good practices in areas in which these reviews are a common practice.
- The study follows the PRISMA guidelines for reporting systematic reviews to meet the highest quality. As a consequence, the SR identifies all the relevant works produced on the topic following an explicit and reproducible research methodology.
- Some recommendations for the control community have been proposed: Normalisation in the information included in the title, abstract and keywords; definition of benchmarks problems to make qualitative comparisons of different estimation techniques; or development of better search engines in the databases, just to mention some of them.

3.6.3. Detected Gaps and Future Research

The SR has discovered important gaps that should be filled in the following years:

- Pure distributed H_∞-based attack detection mechanism: Both papers that incorporate an H_∞-filter for attack detection require a centralized design based on LMIs [45,52]. Providing a decentralized mechanism for the observer synthesis seems to be compulsory, specially in these frameworks in which a cyber-attack is able to disable an agent or its communications.
- Inclusion of matrix gains for consensus-based estimators: Scalar gains [40,46–48,51,55] and diagonal matrices [37] have been proposed in the literature to weight the consensus agreement. Using a complete matrix would be useful to differentiate the weights of the different components in the consensus. Decentralized design of these matrices must also be pursued. In fact, in [45] the authors propose the use of a consensus matrix, but it is common for all the agents and must be found by solving a centralized LMI.
- Modifications of the distributed Kalman filter with reduced communication effort: Either because of the consensus iterations or the need of additional matrices (covariance or information matrices), the proposed DKF are the ones that rely on heavier communication effort to fulfill their objectives. Moving to DKF formulations in which just a subset of the complete state vector is sent should be an interesting goal for the next years.

- Privacy and security in CPS: Some of the primary studies deal with the problem of secure estimation in the presence of attacks (see Table 11). However, nothing has been said about the privacy of the information exchanged between agents. Coping with these issues in an open environment, in which the wireless communications can suffer from any malicious action, must also be analyzed in depth in the future.
- Lack of sliding mode observers and guaranteed estimators for CPS: None of the studies have used this kind of observer structure for the estimation of CPS. While they are very common in the literature, the SR concludes that more effort is necessary in the adaptation of those methodologies that have shown great success in the estimation of nonlinear models.
- Practical absence of estimators for biological, human and animal environments: As examined through the research question 3.1 only two studies have been found with this kind of application. This reveals, in the authors' opinion, that the background of the researchers in estimation of CPS is greater in the cybernetic layer than in the physical one. Increased multi-disciplinary research must be done to fill this gap.
- Almost inexistence of complex models, such as hybrid systems, to describe the physical part of the CPS: While the modelling of complex systems has been the subject of intense research, this SR discloses that those formulations have not been used when the problem of distributed estimation of CPS is to be solved. In fact, most of the studies use linear models [37,40,43,45–49]. Unfortunately, the inclusion of external human commands or the occurence of a discrete event, are better captured with other structures.

In addition, the SR has presented some recommendations to the community, including editors or databases, that were mentioned before.

4. Conclusions

This paper presents a systematic review of the distributed estimation techniques applied to CPS, system of systems and heterogeneous systems that have been published in the period of time from the early 1990s to September 2019. Prior to the report of the SR, a brief presentation of the whole procedure of an SR adapted to our field has been presented.

The studies that have been included have been analyzed to respond to the research questions posed, that is, what are the techniques applied, what are their advantages and limitations and in which field have they been applied. These results have been included in several tables to illustrate the findings. Moreover, the SR has detected existing gaps in the literature and proposed future research lines to the community.

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Appendix B

A distributed set-membership estimator for linear systems with reduced computational requirements

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